CODE to MATTER - Integrating Industrial Robotic Arms: Reconciling the Rapid Advancement of Digital Potentials with a Tangible Physical Existence

Corey J Collier

A thesis submitted in partial fulfillment of the requirements for the degree of:
Master of Architecture

University of Washington
2016

Committee:
Kimo Griggs, Brian Johnson

Program Authorized to Offer Degree:
Architecture

© Copyright 2016
Corey J Collier

University of Washington

Abstract

CODE to MATTER - Integrating Industrial Robotic Arms: Reconciling the Rapid Advancement of Digital Potentials with a Tangible Physical Existence

Chair of the Supervisory Committee:
Associate Professor, Kimo Griggs

Architecture

In the context of digital fabrication in architecture, this thesis is an initial exploration into the use of a 6-axis industrial robotic arm in architectural design. Industrial robots are most commonly known for their use in automation, where the intent is primarily geared towards efficiency and standardization, which neglects the potential for an added value in design. This thesis explores how the symbiotic relationship between the industrial robot arm, human, and material can provide a unique opportunity for design exploration.

The driving concepts for this project are three distinct features of an industrial robot: digital environment, mechanical arm, and end-effector. It will be argued that the second and third of these features are unique to the robotic arm (and absent from other conventional CNC tools). Of particular interest is how these distinct features can influence the way we make and think about design. An industrial robot will be examined through case studies and literature reviews to help illustrate the versatile potential of such robots in the production of architectural elements and assemblies; proposing a potentially efficient, and highly integrated alternative to accepted norms of design/making as it relates to digital fabrication in the architectural design process.

ACKNOWLEDGMENTS

I would like to express the deepest appreciation to my thesis committee, Kimo Griggs, and Brian Johnson for their guidance, encouragement and support. Without their persistent help, this thesis would not have been possible. I would also like to thank all my professors at University of Washington for their dedication and support throughout my entire architectural education. Finally, I would like to thank my wife Lara for her love, support and patience.

TABLE OF CONTENTS

CHAPTER 2 BACKGROUND

CHAPTER 4 CONCLUSION

TABLE OF FIGURES

fig. 3.5 Robot drip painting
fig. 3.6 Three iterations of paint pattern dripped by robot arm
fig. 3.7 Wax study dripped by robot arm
fig. 3.8 Tensegrity using non-linear material
fig. 3.9 Tensegrity winding diagram
fig. 3.10 Tensegrity robot fabrication process diagram
fig. 3.11 Three tensegrity iterations. (L) simplest tensegrity pattern to more complex (R)
fig. 3.12 Robot arm stone cutting fabrication, Italy
fig. 3.13 Real time feedback, credit Sensor and Workflow Evaluations Dubor, et al.
fig. 3.14 Analogue feedback, credit Sensor and Workflow Evaluations Dubor, et al.
fig. 3.15 Robot fiber placement, ICD/ITKE Research Pavilion, University of Stuttgart, 2015
fig. 3.16 Robot fabrication process, ICD/ITKE Research Pavilion, University of Stuttgart
fig. 3.17 Pottery diagram
fig. 3.18 Design of Robotic Fabricated High Rises (2012-2013) Gramazio and Kohler
fig. 3.19 ICD/ITKE Lobster Research Pavilion, University of Stuttgart 2014

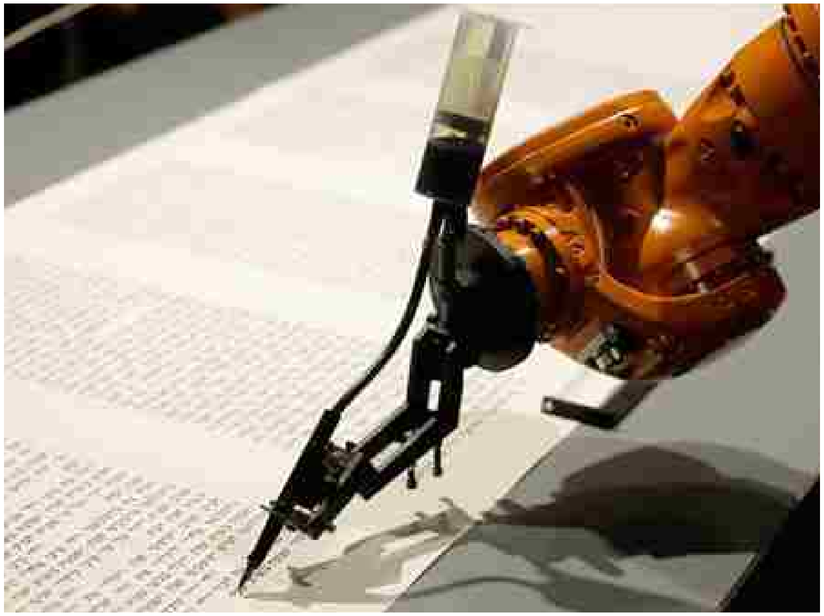


fig. 1.0 Robotic arm writing Torah at Berlin's Jewish Museum (AP Marcus Schreiber)

Introduction

Architects, artists and designers are finding modern articulated industrial robots to be fascinating tools due to their complex kinematics and fluid, nearly human motion. This fascination has renewed and transformed the idea of applying industrial robots to construction and the fabrication of architectural elements.

During the latter half of the twentieth century, robotics in construction and architecture has mainly been looked at from an engineering perspective, with the main purpose of automating the building process (Poppy 1994). These attempts to apply industrialized methods to building processes were primarily geared towards efficiency and standardization (Balaguer and Abderraim, 2008).

In contrast, the recent interest of architects and designers to implement industrial robots is characterized by an approach, which focuses on the inherent versatility of robotics and how this can be introduced at an early stage of the architectural design process. Changing economic and technological conditions support this approach, both in terms of initial costs and the controllability of robotic systems, which have become more accessible over the last decade.

fig. 1.1 Procedural Landscapes, ETH Zurich, Gramazio and Kohler Research

fig. 1.2 Jammed Architectural Structures, ETH Zurich, Gramazio and Kohler Research

In combination with new material technologies, robotics is breaking constraints and creating new opportunities in architecture.

The research projects selected aim to illustrate a range of design interactions between human, industrial robot and material during the design process. The interactions are positioned around different features of the industrial robot, which illustrates how a negotiation between them allows us to explore opportunities that could influence the final result and open the design process toward new possibilities for the built environment.

fig. 2.0 Karel Capek Rossu's Universal Robots 1921 image © Bill Rose

CHAPTER 2 BACKGROUND

2.1 Introduction to Robots

The cultural perception of robotics today has its origins in the popular imagining of science fiction in film and literature. When it comes to imagination, the field of literature offers more creative freedom. Here, robots are not limited by current technology, and can be as imaginative as the creator desires.

Traditionally, robots are depicted as creatures in the mold of a human who is under the control of its creator. This dates back to the origin of the Slavic word 'robota', meaning 'slave' or 'worker', which was first adopted by author and playwright Karel Capek in R.U.R. Rossu's Universal Robots in the early 1920's. In R.U.R. Karel Capek describes the use of artificially produced robot people who are deployed as cheap and disenfranchised workers and who, in the course of the theatre piece, rebel, and destroy all of humankind (Jones, 2004). The word robot has since then made many appearances in popular culture.

One of the first films with a robot-like creation is *The Golem* (1920). In the film, a clay creature of magical origins is created to liberate his Jewish masters from oppression. Similar to R.U.R. (1921) however, the creature turns against its master and tries to kill him. This is a consistent theme in the movie career of robots, the most famous

fig. 2.1 Poster from Metropolis 1926

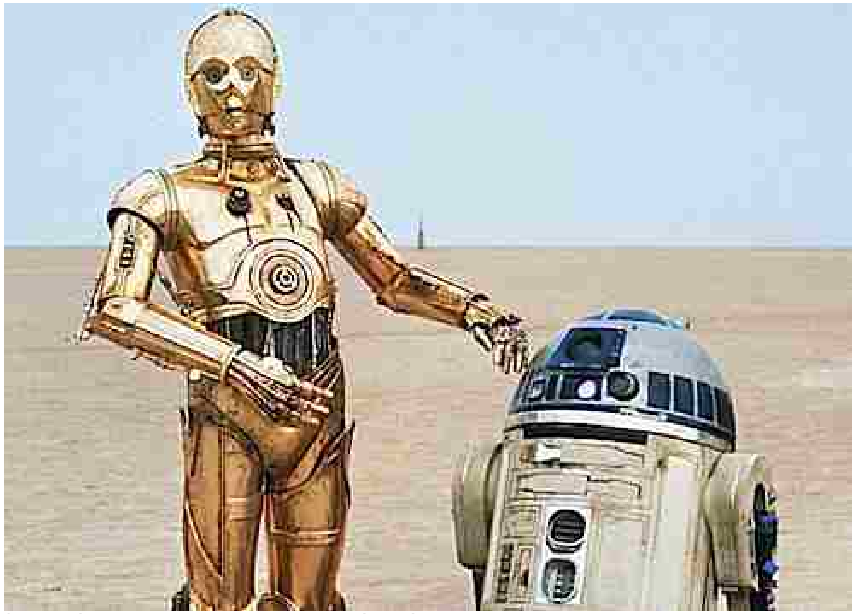


fig. 2.2 Star Wars Movies R2-D2 and C-3PO image The Independent

example of the time being *Metropolis* (1926), where in a futuristic city sharply divided between the working class and the city planners, the son of the city’s mastermind falls in love with a working class prophet named Maria. The city’s mastermind decides that workers are no longer necessary for the city and uses a robot pretending to be Maria to promote a revolution and eliminate the workers.

One of the first robot roles to break the thread of violence was a friendly robot called Robby, who played a side role in the film Forbidden Planet (1956). Robby is a comical character that tries to help the humans in any way possible. His lightheartedness made him adored by children and the public in general. Following suit were the lovable characters from the famous Star Wars Movies (1977). R2-D2 and C-3P0 were both amusing and as such embraced by the audience. They are amazingly intelligent, able to hold full conversations with people, execute difficult engineering tasks that need not only mechanical strength but also brainpower. This was especially exciting after the 1960’s, an era of great technological progress and great fascination with technology.

It is only more recently with the movie Robot and Frank (2012) that a more modern scenario is shown, in which the main character is assisted by a robot who guides him to become a better person. Here the robot is depicted as a collaborator that is able to converse with humans but most importantly to help them perform tasks together.

The concept of a robot has advanced and moved from sci-fi into reality, particularly in the last 50-100 years. In the 1940's science fiction author Isaac Asimov, laid out a set of "laws of robotics" that have greatly influenced the field of robotics (Clark, 1994). These are 1.) A robot may not injure a human being or, through inaction, allow a human being to come to harm. 2.) A robot must obey the orders given it by human beings except where such orders would conflict with the First Law. 3.) A robot must protect its own existence as long as such protection does not conflict with the First or Second Laws (Clark, 1994). While Capek decided robots would ultimately become malevolent and take over the world, Asimov's view of the robot as a benevolent machine, put into the world to serve human kind and ease man's daily struggle, is regarded to have "influenced the origins of robotic engineering" (Wesley, 2004).

In the move from fictional robots to actualized robots, machines were most often intended to carry out a specific task substituting for human labor, especially in hazardous, hard, and exhausting circumstance. This concept is most noticeable at the Argonne National Laboratory, where in 1951 the need to manipulate dangerous radioactive materials led scientists to develop a system for 'teleoperation manipulation'. A set of 'slave' arms would be placed in a remote room holding the radioactive material while scientists perform the task remotely using 'master' arms in a close to real-time scenario. This machine can

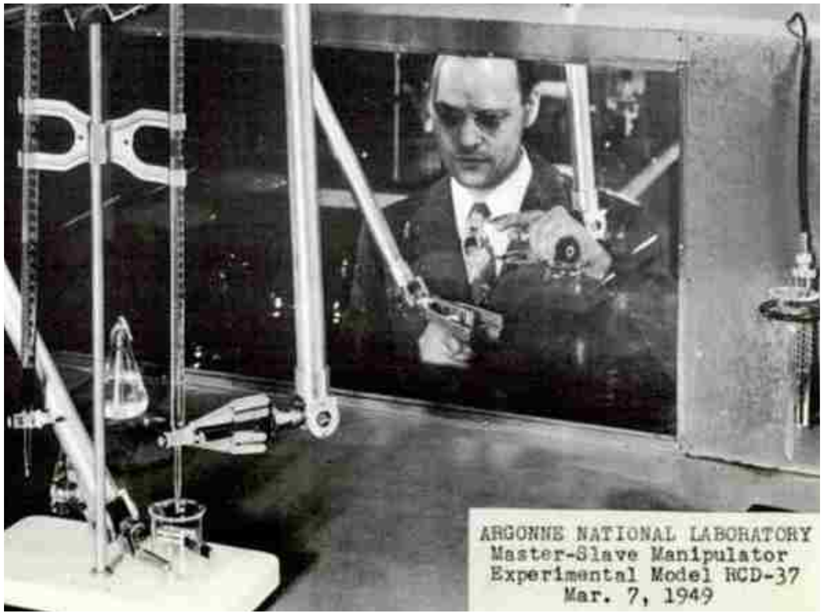


fig. 2.3 Argonne National Labratory Master-slave Manipulator 1949 image Gizmodo

be considered the precursor of modern robotics. In modern industrial robotics, the computer acts as a ‘master’ arm, while the robot acts as the ‘slave’ arm (Corke, 2015).

Industrial robots were not only introduced to solve hazardous problems they were also utilized for large-scale manufacturing tasks. Primarily built to substitute man on particular manufacturing tasks, the industrial robot industry quickly gained momentum and manufacturing was automated in a large-scale in the 1980’s, the biggest customers being the automobile (welding applications) and the electronics industries (assembly applications).

Aside from the many imaginary depictions, “robots are first and foremost computers” (Morel, 2014). Today, it is unclear the limits of what is and what is not a robot, thus creating an on-going debate amongst scientists.

Definitions range from very general to the very complicated and highly specific. The Oxford dictionary defines a robot as “a *machine capable of carrying out a complex series of actions automatically, especially programmable by a computer*” a definition that can easily include printers, blenders, and other appliances. In contrast, Dr. William Gevarter, Program Manager for Guidance and Control NASA, defines a robot as “*a flexible machine capable of controlling its own actions for a variety of tasks utilizing stored programs. Basic task flexibility is achieved by its capability of being reprogrammed. More advanced robots would be capable of setting their own goals, planning their own actions, and correcting for variations in the environment*” (Gevarter, 1985).

For the purpose of this thesis the preferred definition, however, is from robot scientist Peter Corke who writes, “*a robot is a computer that can do things in the physical world*” (Corke, 2015). Within the context of architecture, articulating industrial robot arms can be the ideal link between the physical reality and the digital world that we create.

> “a robot is a computer that can do things in the physical world”
> -Peter Corke

2.2 Architecture

fig. 2.4 Michelangelo Architecture Drawing image michelangelo.net

fig. 2.5 Walter Gropius Torten Estate Dessau, Germany 1926

The modern profession of architecture was invented during the Renaissance, due largely to Leon Battista Alberti. In his influential treatise *De Edificatoria* (1443-1452), Alberti makes a very clear distinction between design knowledge and instrumental knowledge, where the former defines the profession of the architect, and the latter the builder (Witt, 2010). This method of designing and building has essentially remained unchanged for the last 500 years (Scheer, 2014).

In contrast to Alberti, Filippo Brunelleschi's remarkable architectural work took a more holistic approach. His creation of the Florence Duomo combined not just the architectural design of the building, but also the instruments used to construct it: specialized hoists, jigs, and lifts (Witt, 2010). This approach provided an example for architects interested in extending the limits of design through technical invention.

During the Industrial Revolution influential architects such as Le Corbusier, Walter Gropius, and others at the Bauhaus introduced machines to architecture and reinforced the idea that while architects are not usually builders, they cannot remain isolated from the problem of building. Walter Gropius' Torten housing estate in Dessau, Germany (1928) is perhaps one of the best-known examples. The design of a

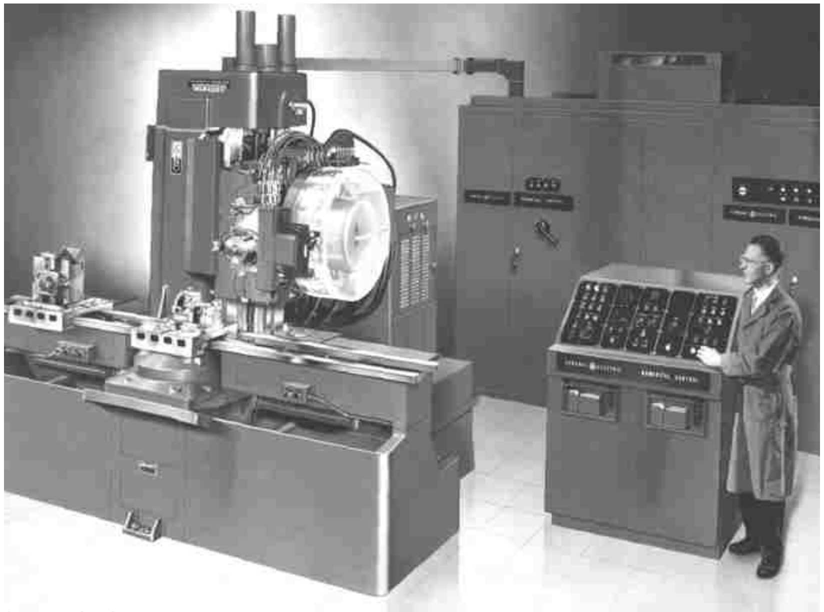


fig. 2.6 CNC Machine 1959- Miliwakee Matic II image cnccookbook.com


fig. 2.7 Honeycomb Morphologies digital fabrication by matsysdesign.com

limited number of identical building elements used to construct slightly different housing types, aimed to enable mass production, and time and cost savings akin to those realized in other sectors of 1920's industry.

Just as standardization had been the driving force for technological innovation and building during the industrial revolution, so called "one-of-a-kind" production, the manufacturing of unique pieces, functions as a driving force in the information age. As early as the 1950's under the initiative of the US military, the first generation of computer-driven machine tools was developed (Ferguson, 1978). These machines made it possible, theoretically, to overcome standardization that had been imperative for industrial mass production. In the following 50 years, as machines became readily available and the electronic controls more efficient, this technology became known as computer numerically controlled (CNC). Transitioning from industrial production techniques to digital fabrication processes triggered a far-reaching change in the production conditions of architecture.

Within current architecture, much of the attraction lies in the ability to facilitate the realization of "one-off" physical objects. The combination of CNC machines and digital design tools allows the designer to directly transfer design information to fabrication tools. This has resulted in the development of different workflows that directly connect designs and

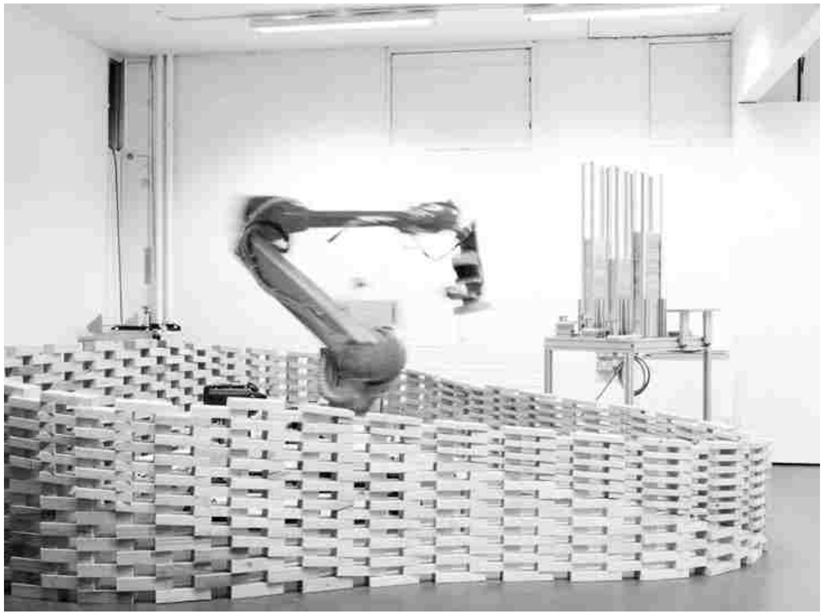


fig. 2.8 Wall assembly process by ETH Zurich

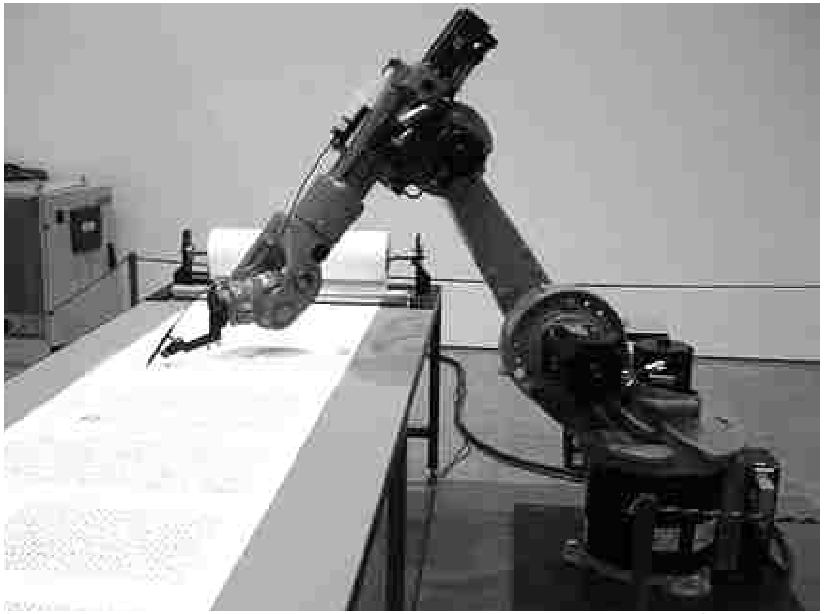


fig. 2.9 Robotic arm writing Torah at Berlin's Jewish Museum (AP Marcus Schreiber)

their realization, escaping from an industry that has thrived through standardization (Gramazio and Kohler, 2014). However, established digital fabrication techniques remain bound at times to their specific manufacturing principles, stemming from traditional mechanic and industrial practices inherited from the mechanical age (Bonwetsch, and Gramazio and Kohler, 2014).

Rethinking the traditional unidirectional flow from digital design to physical production that currently exists in construction and the digital fabrication process, robotic manufacturing has become the next great fascination. The industrial robot, and its decisive distinction from traditional non-standard digital fabrication machines, introduces the possibility for the designer to describe a building part no longer exclusively in terms of it's geometric characteristics, but rather as an 'authored' constructive process (Bonwetsch, and Gramazio and Kohler, 2010). Whereby thinking and making shall not be created in isolation, robotic manufacturing has become a more intellectual problem within the architects' terrain, allowing the architect to push the limits of design through technical invention.

2.3 Robots in Architecture

Within the context of architecture, articulating industrial robot arms can be the ideal link between physical reality and the digital world that we create.

The industrial robot has the distinctive feature that is its *mechanical arm*, which can carry out rapid and highly precise movements to nearly an infinite number of points in three-dimensional space. At the end of this mechanical arm a so-called *end-effector* can be attached. This is the tool by which the respective material process is defined.

In 2005 ETH Zurich was the first multipurpose fabrication laboratory in the discipline of architecture to employ an industrial robot (Gramazio, and Kohler, 2014). The number of robots since then has risen steadily amongst Universities for the purpose of academic research.

Startups like Odico Formwork, RoboFold, Machineous and Rob Technologies along with architectural firms such as BIG, Foster + Partners, and HENN are proving an entirely new and innovative nexus between academic research and the construction industry.

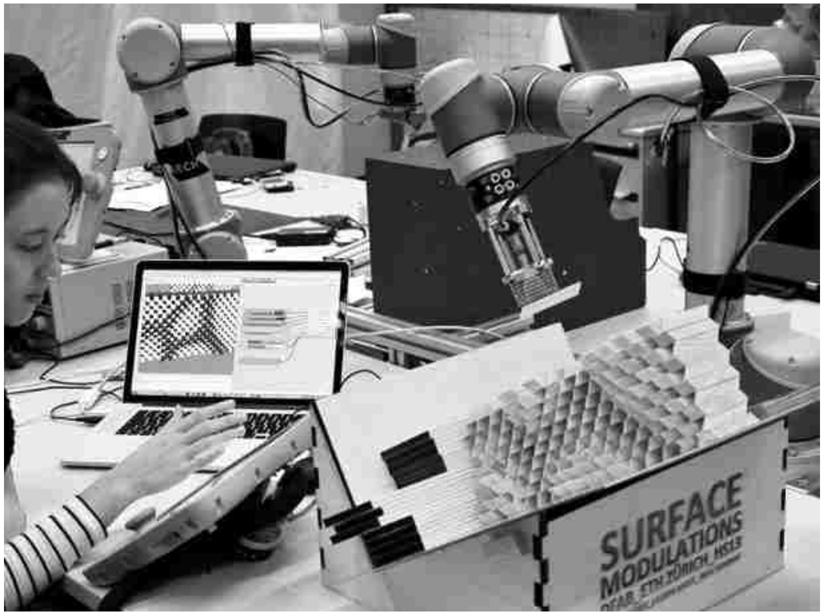


fig. 2.10 FabLab ETH Zurich first to introduce the Robotic Arm in 2005

01	2005
02	2006
03	
04	2007
05	
06	2009
07	
08	2010
09	
10	
11	2011
12	
13	2012
14	
15	
16	
17	
18	
19	2013
20	
21	
22	
23	
24	
25	
26	2014
27	
28	
29	
30	
31	
32	
33	
34	
35	
36	
37	
38	
39	
40	
41	
42	
43	
44	
45	2016

University: ETH Zurich, Switzerland
Installation: 2005

University: Vienna University of Technology, Austria
Installation: 2006

University: Yale University, USA
Installation: 2006

University: Harvard Graduate School of Design, USA
Installation: 2007

University: Royal Melbourne Institute of Technology, Australia
Installation: 2007

University: Carnegie Mellon University, USA
Installation: 2009

University: Graz University of Technology, Austria
Installation: 2009

University: American University of Sharjah, Dubai
Installation: 2010

University: University of Stuttgart, Germany
Installation: 2010

University: University of Michigan, USA
Installation: 2010

University: Mit Media Lab, USA
Installation: 2011

University: Southern California Institute of Architecture, USA
Installation: 2011

University: SEC Future Cities Laboratory, Singapore
Installation: 2012

University: McGill University, Canada
Installation: 2012

University: University College, London
Installation: 2012

University: Delft University of Technology, Netherlands
Installation: 2012

University: University of Innsbruck, Austria
Installation: 2012

University: IAAC, Spain
Installation: 2012

University: Universadad Tecnica Federico Santa Maria, Chile
Installation: 2013

University: University of California, Los Angeles, USA
Installation: 2013

University: Princeton University, USA
Installation: 2013

University: University of Technology Sydney, Australia
Installation: 2013

University: Kent State University, USA
Installation: 2013

University: University of Virginia, USA
Installation: 2013

University: Universadad Adolfo Ibanez/FabLab Chile
Installation: 2014

University: University of Washington, USA
Installation: 2016

fig. 2.11 Robotic arms being used in Universities credit Gramazio and Kohler Research

In the direct application of automation and robot technology in construction, Marshal McLuhan's insight is confirmed: "Every new production medium is first applied in the same way as the previous one, before the technology's actual inherent potentials find expression" (McLuhan, 1974). While robots rapidly became "standard" in industrial automation (Engelberger, 2007), prototypical attempts to introduce robot-based processes in the construction industry failed during the 1990's, both economically and architecturally, largely because the control and machine technologies led exclusively to highly specialized, very expensive and not very flexible construction robots or robot-based building factories (Bock, 2008). Perhaps the reason for this might be that instead of exploiting the versatility of the machine the intention was solely that of automation.

Furthermore, a new building culture was inhibited because it was engineering disciplines such as robotics, mechanical engineering, and construction management that attempted to bring robot-based building automation to the construction site. As a result, the specific conditions of architecture were overlooked in favor of pure automation of manual tasks.

While it is tempting to view the introduction of robots in architecture as a reformation of modernist efforts to transform the field of architecture production into a fully automated and thoroughly rationalized industry, that is not the case. What is underway, however, is the integration of design and production that in combination with computer programming opens up entirely new opportunities for architectural materialization (Gramazio, and Kohler, 2010).

> "every new production medium is first applied in the same way as the previous one, before the technology's actual inherent potentials find expression"
> -Marshal McLuhan

2.3.1 Digital Environment

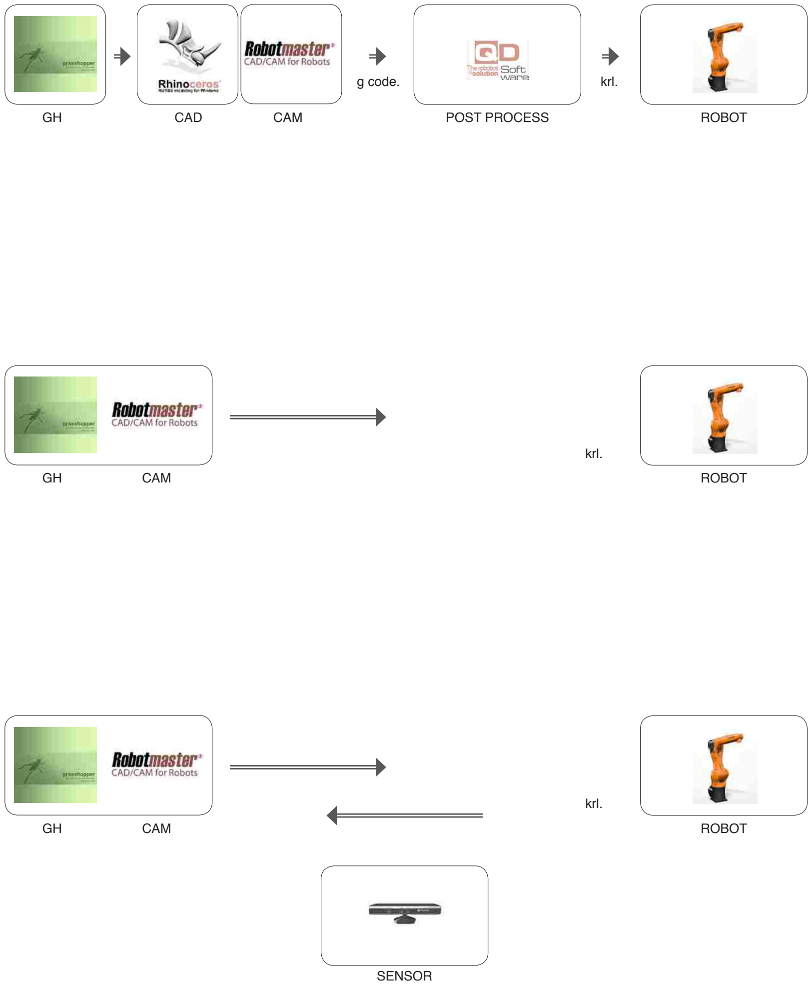


fig. 2.12 Programming Industrial Robot arm workflow- evolving

The industrial robots principal advantage over traditional automation is its programmability, which refers not only to the physical outcome of an object, as is the case with 3D printers, but rather the digital control of its movements and actions. This allows the architect to push the limits of design by gaining control of the fabrication process (Bonwetsch, 2012). Recent advances in computer programming, specifically parametric design, have allowed the architect to push the limits of intellectual work.

Parametric design is a digital technology and geometric modeling software that has gained momentum in many design disciplines and is helping to streamline the digital workflow of industrial robots. Unlike traditional drawing programs, parametric software allows the design to relate to external information. Models can contain enormous complexities that allow integration of dynamic data such as constructive, environmental and logical conditions. Several parameters can adjust the model simultaneously, generating dozens or even thousands of related but distinct forms (Lagios, 2010). In other words, it is a way to explore possible designs when the final outcome is not precisely defined, resulting in a shift from object design to process design (Reinhardt et al. 2016).

Using a parametric visual programming environment such as the Grasshopper plugin for Rhino to process data and communicate with industrial robots gives designers access to tools and languages that control both the design and robot movement simultaneously (Braumann, and Cockran, 2009). Recent initiatives have made this technology feasible by integrating computer-aided manufacturing (CAM) into parametric software. KUKA|prc, Virtual Robot, and Scorpion are all examples of plug-ins for Grasshopper that combine these technologies. An additional advantage to this software is the visual programming environment. By varying parameters within a predefined process, one is able to learn from visual results and move quickly through iterations without having to go through multiple export/import steps from CAD to CAM to robot.

Additional robot programming tools that work inside architectural CAD software have been developed over the years. Jason K. Johnson and Andrew Payne published Firefly, a plug-in that allows Grasshopper to interact with physical computing microcontrollers, digital 3D scanning and image capturing technologies such as Kinect, Skanect, 123Dcatch. These external sensory devices can capture information about the physical model and send it back to the design environment, allowing the architect and the computer to analyze the data before initializing the next move creating a bidirectional flow of information.

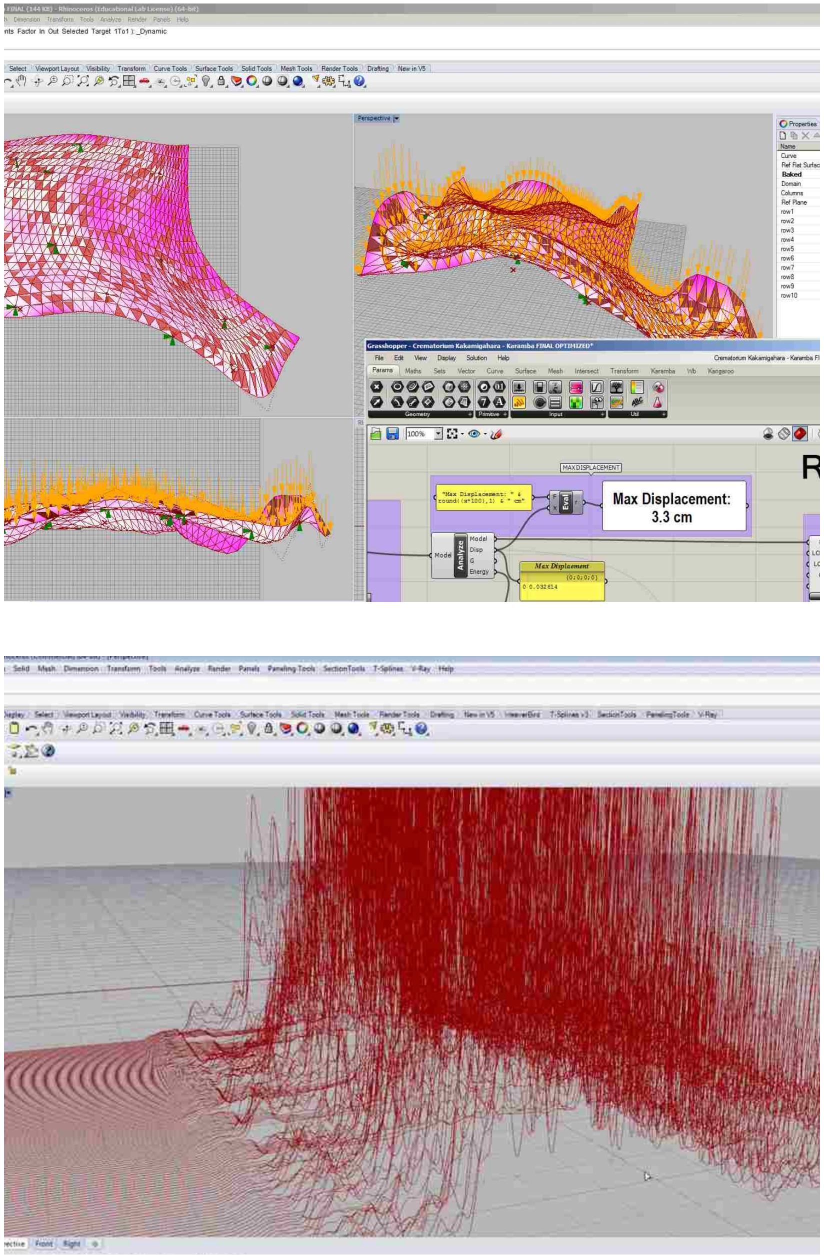


fig. 2.13 Programming Industrial Robot arm using various digital data within CAD

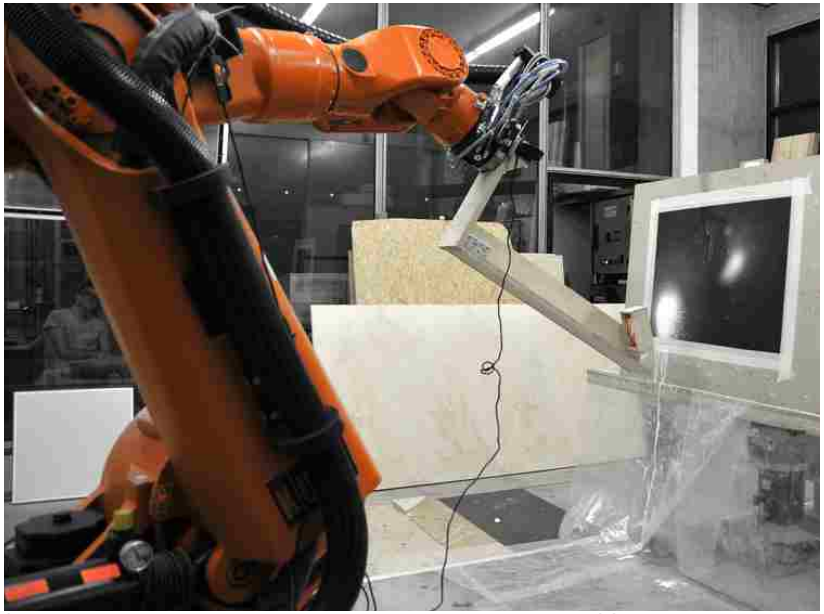


fig. 2.14 online robotic control robot workcell credit University of Stuttgart

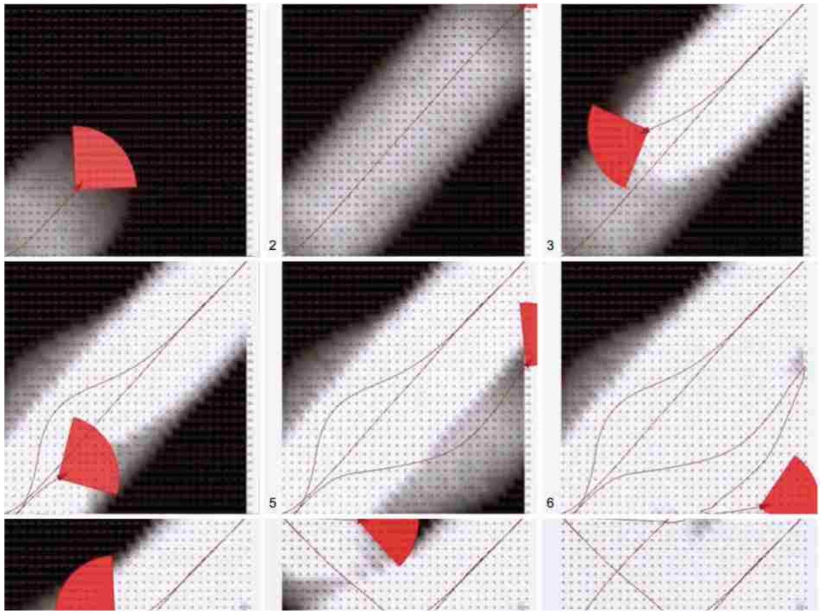


fig. 2.15 online robotic control digital path credit University of Stuttgart

Note for example, Online Robotic Control, University of Stuttgart. The project is an ongoing research study on the design of online control methods for robotic fabrication. The experiments presented deal with the possibility of creating a bridge between the digital and the physical through real-time integrated feedback sensors. Spray paint is used to draw an interactive and adaptive path on a sheet of black paper. The process is visually recorded and informs the path along the way. The robot moves along the canvas to fill the black space with white spray paint, while it is recalculating and adapting its path with each scan. The digital workflow incorporates Rhinoceros with Grasshopper, quokka plug-in for Kinect sensor, and Firefly, which relays data from the Kinect sensor back to the robot.

2.3.2 Mechanical Arm

Another distinct feature of the industrial robot is its articulating mechanical arm. A “kinematic chain” of rotational joints, the robot is capable of carrying out rapid and highly precise movements reaching nearly an infinite number of points freely in three-dimensional space.

Kinematics is used to describe the motion of a system of jointed parts (multi-links), such as engines, robotic arms or the skeleton of the human body (Biewener, 2003). This kinematics chain of the industrial robot creates a fluid, close to humanlike motion, which lends itself particularly well to assembly. Assembly implies building up a three-dimensional element out of a number of single pieces that are smaller than the final object. The single pieces constituting the final object have to be placed and processed in a certain order to guarantee the feasibility of the production, in principle; the same logic applies to traditional, manual construction. This puts robotic fabrication close to actual building practice, as construction can be described as the assembly of different parts and materials (Lynn, 2008).

Note for example, the Future Cities Laboratory (FCL) at the Singapore-ETH Centre for Global Environmental Sustainability (SEC), where they introduced the research project ‘Design of Robotic Fabricated High Rises’ (2012-2013) led by Fabio Gramazio and Matthias Kohler. In the studio, students demonstrate how computer programming and robotic fabrication can be used in design, both conceptually and methodologically. This begins to illustrate how robot-assembled models begin to shifts the focus from designing form to designing the process. Robotically fabricated models bring into focus structure and tectonic characteristics. The flexibility of the robots arm give the architects direct and physical means to study and understand the three-dimensionality of their designs, by directly connecting the physical model with its computation origin.

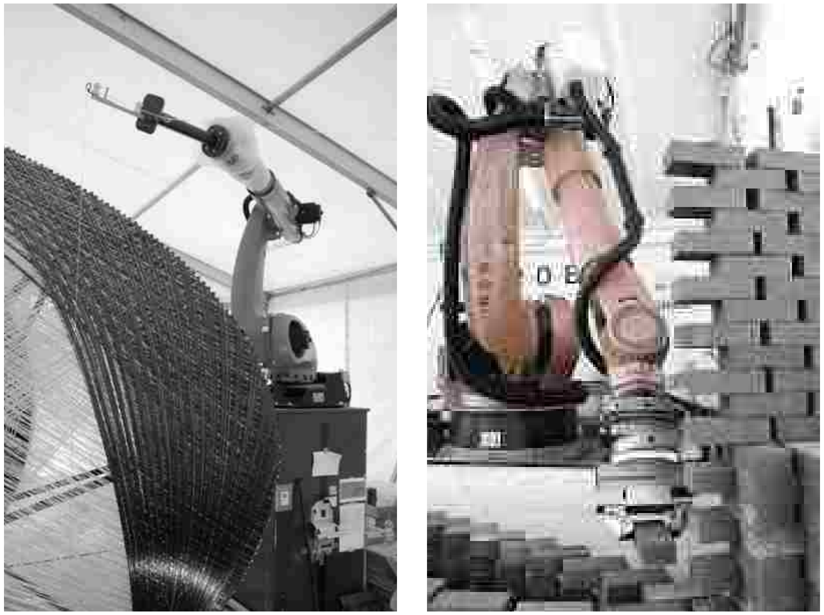


fig. 2.16 various assembly processes utilizing flexibility of robotic arm

2.3.3 End-Effector

At the end of this “kinematic chain” of rotation joints a so called “end effector can be attached. The end-effectors can be highly customized and can be changed within a running process. End-effectors can be designed to perform a physical material manipulation, or to gather data, for example by probing, scanning, or measuring. This is the tool by which the respective material process is actually defined. Industrial robots are distinguished by their versatility. Like computers, they are suitable for a wide variety of tasks because they are ‘generic’ and therefore not tailored to any particular application (Gramazio and Kohler 2014).

In architectural practice, materials have traditionally been used to construct a built version of an idea that was determined in advance. Designs after conception are subject to complex processes of rationalization where tension occurs between the material and the form due to the initial disassociation between them. Additionally, design usually follows their initial path, disregarding any information that the material might have been trying to add during the formation process, this has resulted in a linear, unidirectional flow of information. (Bechthold, 2010).

The ability to gather data, through a specifically designed end-effector, can provide information about the robot’s work environment, the physical model, or material behavior and send it back to the design environment through sensor feedback creating a bidirectional flow of information. This introduces the notion of material exploration in the conceptual phase of the design process, which gives us a deeper understanding of material behavior. This allows craft as an approach to making rather than as a specific way of making (Sennet, 2009) to become an active agent during the design and materialization process. As Lambros Malafouris states in his essay, “At the potter’s wheel”, material agency is not something inherent in the material itself, but as a relational, emergent property that develops through engagement with the material, as can commonly be seen in craft processes.

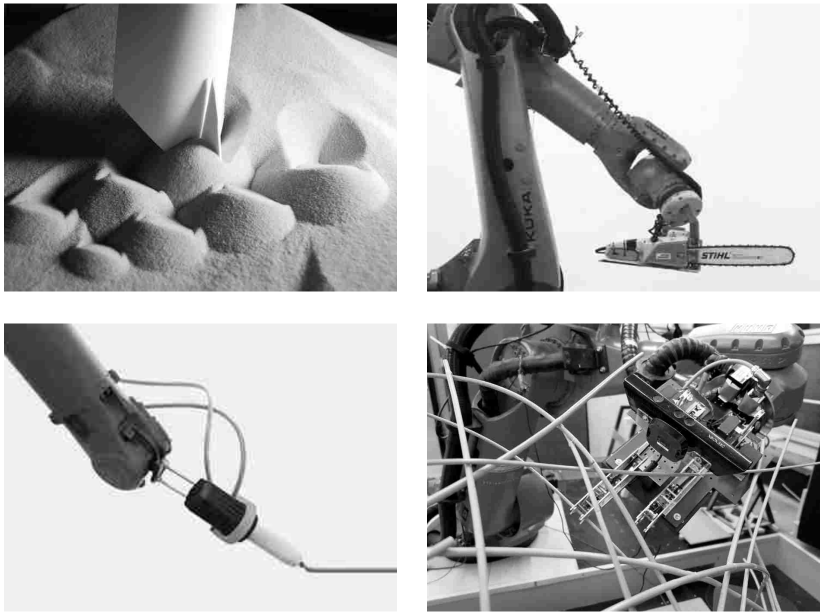


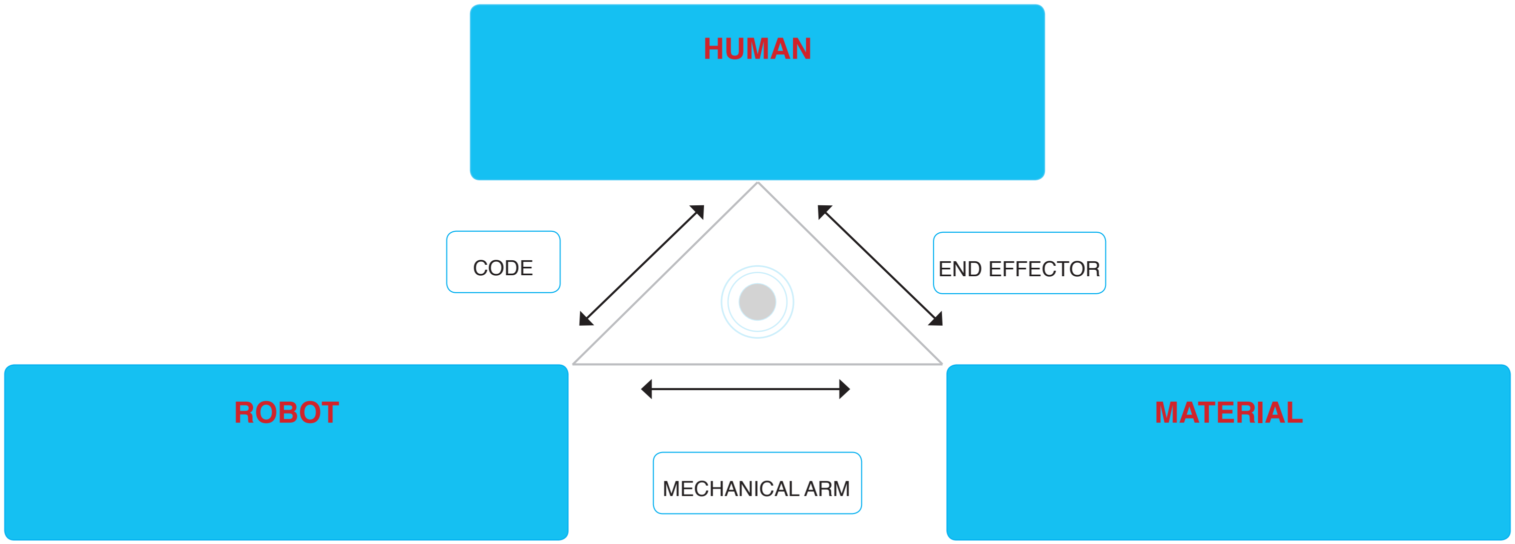
fig. 2.17 various material processes defined by custom designed end-effector

CHAPTER 3: RESEARCH PROJECTS

The robot fabrication process is composed of code for controlling the robot's mechanical arm, and from the 'specific' characteristics of the end-effector that are applied. The 'generic' kinematics of the mechanical arm and 'specific' end-effector fundamentally distinguishes the industrial robot from all other conventional computer numerically controlled (CNC) machines. Furthermore, this creates a multi-dimensional negotiation, which purposes a holistic approach to making that successfully incorporate machines, humans, and material agencies throughout the process.

The research projects selected aim to illustrate a range of design interactions between human, industrial robot and material during the design process. The interactions are positioned around different features of the industrial robot, further illustrating a complex negotiation and how it may allow us to explore opportunities that could influence the final result and open the design process toward new possibilities for the built environment.

fig. 3.0 Diagram representing symbiotic relationship involved for robot fabrication



3.1 Transduction


fig. 3.1 Robot path based on grayscale values of sampled raster image

The case study titled “Transduction” was intended to gain a better understanding of the direct relationship between programming code and the robots movement through representation.

Sampling a raster image for its grayscale color value was the method used for choreographing the robot’s movement. A series of points were given a numeric value between 0 and 1 based on the grayscale of an image. Unlike conventional machines that have a defined use, a robot arm cannot do anything without designing its tool or end-effector. A marker and paper where chosen as the medium for this study, thus the end-effector was designed accordingly to hold the marker. The points, which were given a numeric value, could now be manipulated according to the material. For example, moving the points in the ‘Z’ direction would change the pressure of the marker while a rotation command would change the thickness of the line (a chisel-point marker was used in this experiment). Both rotation and pressure manipulations were attempted, running in a back and forth pattern. The robot followed instructions with precision and accuracy yet it wasn’t until the designer intervened by adjusting the marker pressure, location, and line spacing that the image began to appear.

Applying the principles of the pressure study, the path was changed from a linear to a radial direction moving from the center of the image outward. Interestingly, an entirely new graphic appeared. With no sign of the initial image it became evident that while there is a direct relationship between path generation and the robots movement, the image provided only data for creating the robot's path and not a direct translation of information from the image. This forced the designer to think about the steps and the final result that he wanted to accomplish in order to decide how to plan the robot's movement, create the code, and optimize its output.

Through sampling techniques within a CAD environment, this research study introduces the notion of path-based processes rather than object-based. This technique of sampling an image can be applied similarly to analytical studies such as solar, light, sound, or structural optimization to determine a path. Furthermore, the tool and material may also be exchanged while using the same file. The final outcome allowed for a better understanding of the tool, realizing that a series of parameters has to be considered from the early stages to have a successful and direct connection between design parameters and physical output. The designer becomes an editor of the generative parameters of the system, as set out at the beginning. By controlling the digital and physical parameters for its generation, these parameters hint of the output without directly designing the final product.

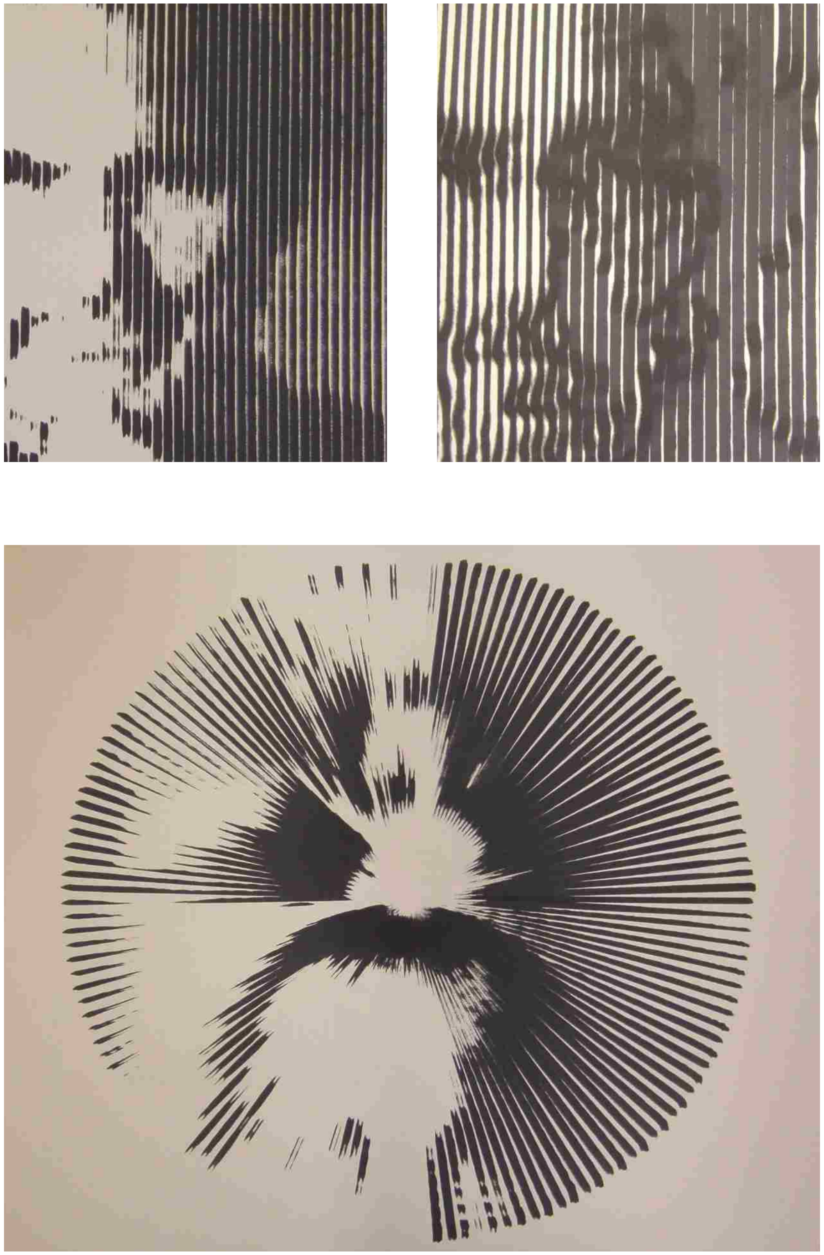


fig. 3.2 Robot path based on grayscale values of sampled raster image

The Ganteinbein Vineyard Façade, by Gramazio and Kohler is an example of an additive robot fabrication process utilizing the same principles as the transduction study. Numeric values based on the grayscale of an image are used to instruct an industrial robot arm to place and rotate a series of bricks creating an articulated pattern for a wall assembly. Rather than adding complexity and variation to the brick, the complexity and variation were added to the digitally controlled process.

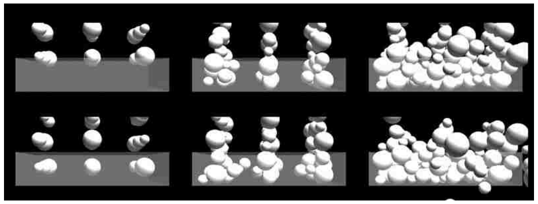


fig. 3.3 Gantenbein Vineyard Fascade, Flasch Switzerland, Gramazio and Kohler

fig. 3.4 Robot brick assembly construction, by G&K

3.2 Fluidity

The case study titled, ‘Fluidity’ attempts to explore materiality through exploiting the humanlike motion of the robotic arm.

In this study a series of curves were created to push the extents of the robot’s flexibility and range of motion. While singularities created limitations, a negotiation between the series of curves and the range of motion of the robotic arm determined the final path. This allowed for the design to be adjusted until the desired robot tool path was achieved. Paint was used to materialize the motion of the industrial robot such that a unique pattern that was not predetermined appeared. Two proceeding iterations were attempted resulting in very similar outcomes, highlighting the accuracy and fluidity of the robot’s movement. The author wanted to expand upon this study by introducing an alternative material in an attempt to explore three-dimensional space. Wax, a phase changing material was used. Wax allowed for the process to be repeated in the same fashion, building three dimensionally as the material solidified.

A unique feature of this fabrication process is that these pieces were created without the robotic arm physically touching the object or work surface, unlike the previous study where a negotiation took place to precisely align the marker and the paper to realize the image. The robot’s path was accurate and precise each time, the material, however, created subtle variations between each interaction. This lends itself to more of a handmade process than a machine one. The variability of material begins to distort or confuse the sign of the original archetype and, as a result, conceal the identity of the author, or make it irrelevant (Carpo, 2011). The idea of varied outcomes, which are not possible to describe through a digital model, leads to the notion that while the robot can work with material that yields uncertain results, the material itself can also influence the design with opportunities that may have otherwise been missed.

fig. 3.5 Robot drip painting by author

fig. 3.6 Three iterations of paint pattern dripped by robot arm

fig. 3.7 Wax study dripped by robot arm


fig. 3.8 Tensegrity using non-linear material

3.3 Winding Space

Wanting to have more control over the movement of the robotic arm, and finding inspiration in winding and weaving patterns, this case study explored assembly processes utilizing these methods.

A simple tensegrity structure was chosen for this experiment. The end-effector was designed to hold 3 compression struts such that the robot could position each end-point of the strut at the location of the string source. The robot would then rotate around the string source in the ‘Z’ axis looping the string around the end. It would proceed by moving to the next end point until all ends were connected and no tension lines were repeated. The robot posed great limitations on the number of struts and orientation due to reachability, which resulted in a very restricted, symmetrical object. The object lacked interest, and uniqueness so alternative materials were tested. With the ability to custom design the end-effector; an organic non-linear material was scanned using a 3D scanning technology. By knowing the location of the strut endpoint a Grasshopper file was created to determine the pattern and sequencing of the assembly.

Utilizing the precision of the robot and 3D scanning technology created an opportunity to transform randomly changeable, organic non-linear materials into predicable results. Similarly, other digital tools could also enable the structural use of new, non-linear materials, which may be structurally unpredictable due to natural variation. Nonstandard technologies could interact with such irregularities, and adapt form and design to the variability of nature almost as aptly as artisanal manipulation once did.

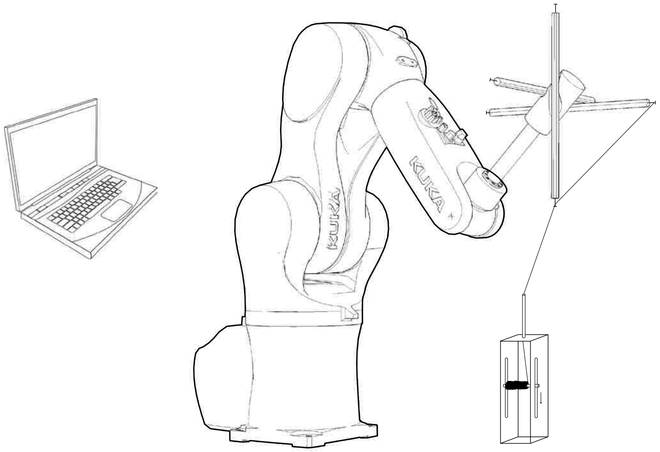


fig. 3.10 Tensegrity robot fabrication process diagram

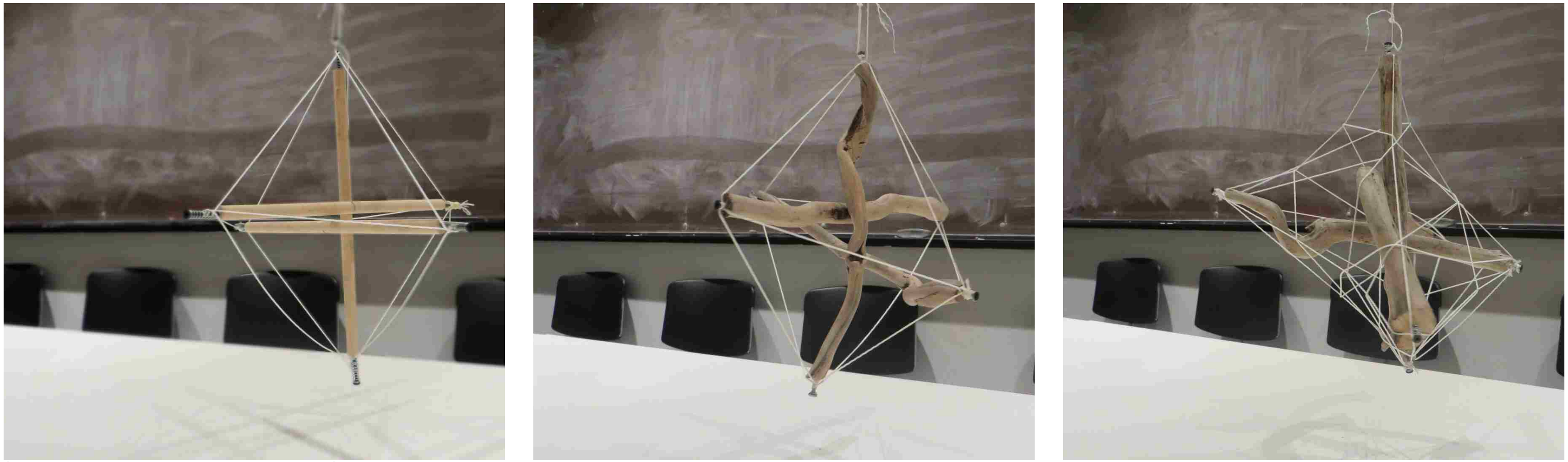


fig. 3.11 Three tensegrity iterations. left; simple structure to more complex right

> “opportunity to transform randomly changable, organic non-linear materials into predicable results” -Mario Carpo

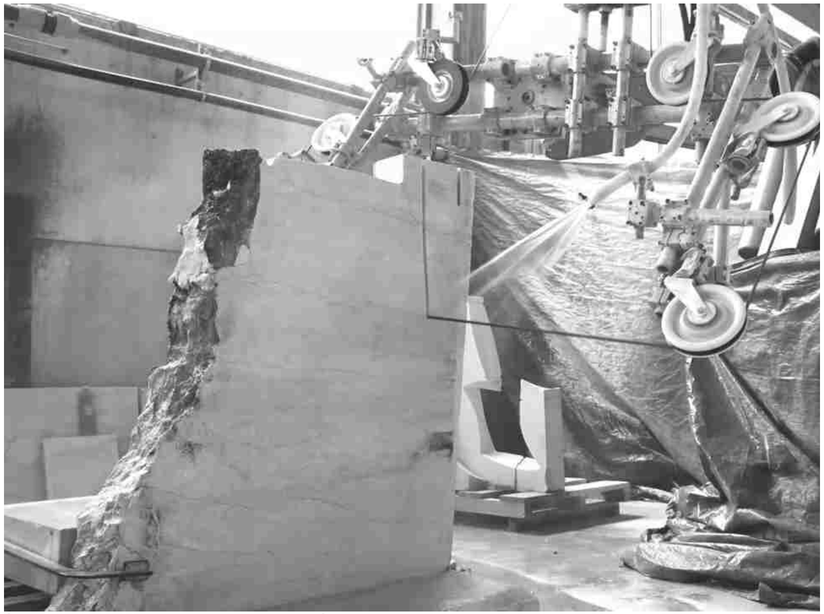


fig. 3.12 Robot arm stone cutting fabrication, Italy

CHAPTER 4 CONCLUSION

4.1 Discussion

Aiming to illustrate a range of design interactions between human, industrial robot, and material, the author chose to focus on three features unique to the industrial robot. Exploring programming code, mechanical arm capabilities, end-effector, and materiality, it became very apparent that an intrinsic interconnectedness existed. One cannot investigate the infinite possibilities of the mechanical arm without also considering materiality, the end-effector and code for operation. Just as one cannot attempt coding the robot without first considering the material to be explored. This symbiotic relationship allows us to explore opportunities to create new aesthetic languages for our built environment.

Furthermore, the interaction between the designer and the robot can take place at different stages of the design, from early phases of the design process to on-site construction situations. Using a robot forces architects to think systematically about what they are doing and to mechanize the complexity of craft and other manual tasks, which are normally taken for granted. The distinct affordances of the robotic arm, which requires a negotiation, allows for an adaptable evolving framework maintained by material behavior and feedback loops to emerge.

Feedback occurs when outputs of a system are routed back as inputs creating a circuit or continuous loop, which can occur in various lengths of time. Digital technologies are allowing for processes to be interrupted by ‘real-time’ feedback based on material behaviors. For example digital 3D scanning, sensors and image capturing technologies can provide information to the design environment about material behavior, the physical model, or the robots working environment. The extracted information can then be sent back to the robot to act upon it through a feedback loop. This creates processes where the architect sets the various parameters based on fabrication techniques and material properties and adjusts them iteratively in the physical and digital models, until a balance between material properties, technical requirements and aesthetics is reached. One could argue that this is in fact similar to craft processes.

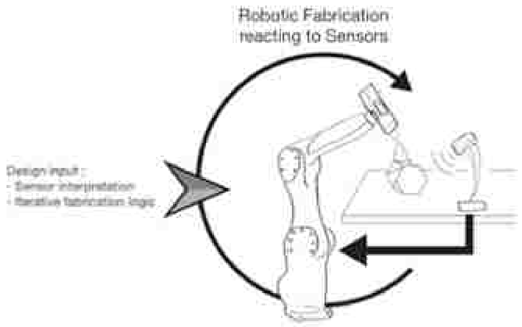


fig. 3.13 Real time feedback, credit Sensor and Workflow Evaluations Dubor, et al.

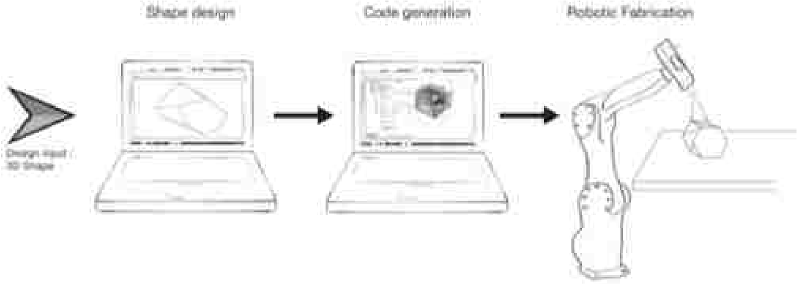


fig. 3.14 Analogue feedback, credit Sensor and Workflow Evaluations Dubor, et al.

fig. 3.15 Robot fiber placement, ICD/ITKE Research Pavilion, University of Stuttgart

The ICD/ITKE Research Pavilion at the University of Stuttgart is an example where real-time feedback was used similarly to that of a craft process. A pneumatic formwork is inflated on site. A carbon fiber filament is placed on the bubble from the interior based on a pattern determined by a structural simulation. The formwork fluctuates during fiber placement, thus the position of the robot end-effector and contact force is constantly adjusted and guided via a sensor system, redirecting each path thus creating an adaptable fabrication process.

fig. 3.16 Robot fabrication process, ICD/ITKE Research Pavilion, University of Stuttgart

fig. 3.17 Pottery diagram

4.2 Opportunities

Traditional craftsmen, unlike designers, do not send blueprints to factories or building sites: they make with their hands what they have in their mind (Carpo, 2011).

Similarly, the current status of robots in architecture is beginning to provide a new sense of ‘intimacy’ between the designer and his or her tools, and using the materials similar to those, which painters and sculptors have enjoyed, yet with precise digital control. Through a negotiation between human, robot and the material the architect becomes a designer of processes that interfaces between the virtual and the physical, making design and structural decisions as an editor of constraints for their interaction. This allows architects to mix craft and tools in an intellectually meaningful way, creating a trinity of material, technology, and form (Lynn, 2006).

The role of the robot in architectural processes is still ambiguous, however, based on Asimov’s laws of robotics, different degrees of robotic participation in the design process are envisaged. The robot not only obeys orders based on code, but can also elaborate upon them, contributing technical expertise towards the design intention. The robot guides the process of formation with precision and control of complex three-dimensional digital geometry.


fig. 3.18 Design of Robotic Fabricated High Rises (2012-2013) Gramazio and Kohler


fig. 3.19 ICD/ITKE Lobster Research Pavilion, University of Stuttgart 2014

The three case studies demonstrate a number of interactions between human, robot and material and the collaborative negotiation that takes between them. Robot fabrication holds the potential for rethinking the role of the architect in the design and fabrication process. It allows for the creation of a new professional role for the architect that combines critical thinking while taking advantages of new tools, technologies and agency interactions collaboratively creating greater design that would be nearly impossible otherwise.

BIBLIOGRAPHY

Bock T. (2008) *Construction Automation and Robotics*, in Robotics and Automation in Construction

Balaguer C. and Abderrahim M. (2008) *Trends in Robotics and Automation in Construction* Robotics in Automation and Construction, In-Tech

Bechthold M. (2010) GSD research. *The Return of the Future*, A Second Go at Robotic Construction.

Biewener A. (2003) Animal Locomotion, Oxford University Press

Bonwetsch, T. (2012) (Robotic Assembly Process as a Driver in Architectural Design

Braumann, J & Cokcan, S. (2011) Digital and Physical Tools for Industrial Robots in Architecture: Robotic Interaction and Interfaces

Carpo, M. (2011) The Alphabet and the Algorithm, MIT Press.

Clark R. (1994) Asimov's laws of robotics: Implications for information technology. Part 2, Computer 27, no1 (1994)

Corke P. (2015) *Introduction to Roboti,.* Robotics Vision and Control, Springer

Engelberger J. (1999) Historical Perspective and Role in Automation.

Ferguson C. (1978) *A history of numerically controlled machine tools*. CME

Gevarter, W.B. (1985) *Intelligent Machines*: An Introductory Perspective of Artificial Intelligence and Robotics

Gramazio F. and Kohler M. (2014) Research at ETH Zurich. *Made by Robots*. Challenging Architecture at a Larger Scale. Wiley AD. May/June 2014

ISO 8373:2012 Robotics and Robotic devices – Vocabulary

Iwamoto L. (2014) *Digital Fabrication*. Architectural and Material Techniques. Princeton Architectural Press.

Jones, C. (2004) *Rossum's Universal Robots*. New York: Penguin Books, 2004

Lynn G. (2006) *Architectural Design* Vol. 76, no.4 (2006)

McLuhan, M. (1974) *Understanding Media*: The extensions of Man. London Abacs, 1974

Morel, P. (2014) *Computation or Revolution.* Made by Robots: Challenging Architecture at a Larger Scale. Wiley AD. May/June 2014

Poppy W. (1994) Driving forces and status of Automation and Robotics in Construction in Europe. Automation in Construction 2, No4

Reinhardt et al. (eds.), Robotic Fabrication in Architecture, Art and Design 2016

Sennett, R. (2008) *The Craftsmen.* The special human condition of being engaged. New Haven: Yale Press

Sheer D.R. (2014) *The Death of Drawing Architecture in the Age of Simulation*. 2014

Wesley, L. (2004) *The History of Robotics*. Robotics and Automation Handbook. CRC Press

Witt, A.J. (2010) *A Machine Epistemology in Architecture*. Encapsulated Knowledge and the Instrumentation of Design 2010