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Abstract

Throughout an extensive period of time, advanced mechanical tools such as robotic arms have been a common prospect in many production industries. Today, and as the potentials in digital design and fabrication technologies are seen to enhance complex tridimensional construction processes, robots are rapidly being integrated within the architectural education curriculum. In a relatively short amount of time, many architectural faculties around the globe have set up experimental digital fabrication laboratories with 3D printers, CNC machines, and robotic arms. This paper will argue the use of robots in education beyond the opportunities provided by the already traditional automated modes of fabrication, trying to appreciate design and fabrication methodologies as open interfaces that challenge students with problem-solving, advanced geometry, and programming.

Keywords

Design Education, Robotics, Digital Fabrication Laboratory, Digital Tools, Open Interfaces

Interfaces Expanding Boundaries of Architectural Design Education with Industrial Robots

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ABSTRACT

Throughout an extensive period of time, advanced mechanical tools such as robotic arms have been a common prospect in many production industries. Today, and as the potentials in digital design and fabrication technologies are seen to enhance complex tridimensional construction processes, robots are rapidly being integrated within the architectural education curriculum. In a relatively short amount of time, many architectural faculties around the globe have set up experimental digital fabrication laboratories with 3D printers, CNC machines, and robotic arms. This paper will argue the use of robots in education beyond the opportunities provided by the already traditional automated modes of fabrication, trying to appreciate design and fabrication methodologies as open interfaces that challenge students with problem-solving, advanced geometry, and programming.

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1. INTRODUCTION

In a very short period of time, especially during the last decade, architectural education has witnessed the introduction of automated industrial tools in the field. Among Computer Numerical Control (CNC) machines, laser cutters, and 3D printers, the robotic arms, known as industrial robots, have opened endless boundaries in the fabrication of special architectural components. Conceptually, the labor of such tools has been widely explored throughout the history of architecture, especially when focusing on the 20th century. Visualizing the Walking City as Archigram did in 1964 is almost close to possible nowadays. (Cook, 1999) As of today, the use of robotic arms is reaching extreme levels of architectural creative productivity, as for example with the development from MX3D of an ornate metal bridge for Amsterdam that will be 3D printed with robotic arms. (Naboni and Paoletti, 2015) In addition, the actual procedures using industrial robots in architecture covers a considerable range of high tech tools varying from CNC machines to sensors. Therefore, endless possibilities are ahead of the architectural education and practice with industrial robots.

Regarding the functionality principles of robotic arms, they are considered to be used as multifunctional and precise tools in a variety of industrial fields, following certain modularities to concretize different tasks, according to orders or intentions. Tasks are defined and then executed according to the tool that is mounted on the robot's flange. Such procedures are similar to the behavior of human dealing with the tasks, using the proper tool for each job. One robot can therefore perform a series of procedures using diverse methodologies and tools, replacing the need for a series of machines. Industrial robots can therefore play an important role in the architectural field, both at the educational and professional practice levels, by optimizing construction processes, time and costs. Robots may also help to push designers' intentions concerning creativity, visualization of real prototypes, and non-standardization. In addition, as the sizes of such machines allow for the production of larger scale components, it is possible to deal with architectural design and fabrication challenges at real scale.

Basing the argument on issues such as scale and flexibility, it is interesting to appreciate that most robotic based projects in the architectural contemporary arena are being carried on as versatile real scale experiments of direct implementations. In 2012 for instance, Gramazio Kohler Architects and Raffaello

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D'Andrea collaborated with ETH Zurich to program drones to lift and stack standard polystyrene bricks to form a non-standard structure at the FRAC Centre on Orléans, France. (Gramazio and Kohler, 2008) This was the first time that flying machines were programmed to build architectural components. The procedure was realized as a prototype since the material in question was not considered to be of structural features related to the formal complexities into question. However, this was a first step to suggest the use of drones for the construction of actual buildings. As of today, they are machines that can collaborate in building structures, showing that they can actually work on a building scale.

In a versatile mode of either standard or non-standard fabrication, industrial robots can be used to execute jobs varying from brick-stacking to multi-axis milling materials, according to the tool that is attached to it. The advantages and impacts that such a versatile machine can have on architectural education have yet to be figured out, organized and discussed in depth.

Throughout the experience encountered in the process of instructing students on the use of digital tools and robotics in architecture, a series of significant general aspects have been detected. Intuition however can be explored in ways that allow students to interact with digital design and fabrication tools. Machines therefore should not be seen as merely tools for fabrication purposes, but rather as potential tools offering models such as the open experiments interface in architectural education (Fig. 1).

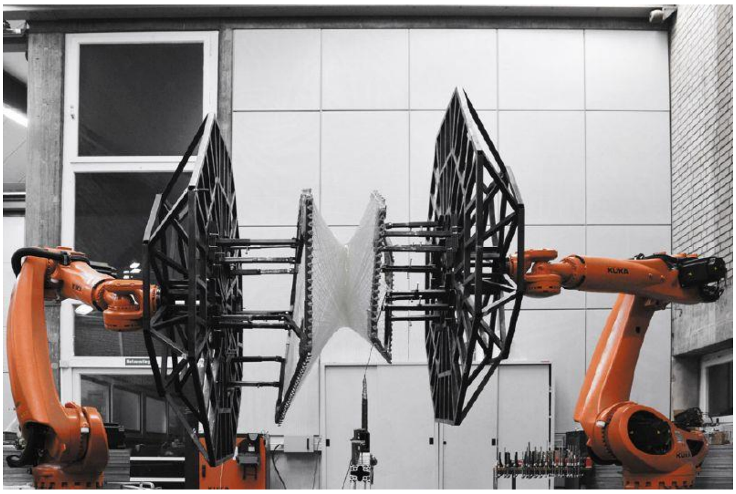

Fig. 1. Tridimensional form finding with carbon fiber structures using industrial robotic arms at the University of Stuttgart

2. CHALLENGES IN COMPLEX GEOMETRY AND ROBOTICS AS APPROACHES IN ARCHITECTURE

Among the many complex tasks implicated in the transformation of digital data into analogue components, the translation of tridimensional surfaces of no thickness mathematically defined is one of the procedures providing the greatest amount of challenges and constraints. The non-uniform rational B-splines (NURBS), defined either aesthetically or mathematically according to design parameters, and sometimes in easy manners according to the simplicity of digital platforms, is one of these examples that usually lack volumetric definitions within the Computer Aided Architectural Design (CAAD) procedures. Due to the user friendly features, in addition to the mathematically embedded procedures available in softwares such as Rhino to calculate surface fluidities, CAAD tools have greatly advanced in ways that allow users to define more complex, precise, and detailed virtual structures of advanced complexity levels.

Such designs coming as a result of special tridimensional relations generating surfaces, or merely lofts or curve networks either with perimetrical tridimensional data or transitional ones, with results lacking volume, were a problem until the popularization of the 3D printers. The digital revolution was a speedy integration process of both digital and fabrication tools. However, and along the way, architects were appreciating the wonders of highly complex forms with the frustration of not being able to translate them into the physical realm. This was mainly due to the lack of a rational system that links the virtual with the physical. And even at the beginning of the implementation of digital technologies in architectural education, such trend was being carefully observed with skepticism. Architects do not

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necessarily need to solve highly complex mathematical problems to generate surfaces, but at least they need to recognize the repercussions of geometric operations.

Among the different automated ways to translate surfaces into volumes, the easiest one is by a simple offset operation. However, the operation in polysurfaces, or a series of surfaces intersecting and articulating among themselves, provides a greater problematic. And despite the fact that only developable surfaces can be geometrically offset in an accurate manner, there is an urge to abide by non-standard geometric CAD software or advanced plug-inns to compensate geometric deficiencies of CAAD tools to fulfill the constructability procedure of arbitrary surfaces.

For education, good ways of spotting such issues in time are digital modeling, model making, fabrication, and prototyping. Such procedures help students to grasp rationalization and optimization procedures for the digital transformation of complex surface articulations into analogue matters. In research and teaching, the work with machine tool path layouts can incorporate fabrication restrictions as design parameters for the creation of surfaces and solids using digital tools which are extremely useful. The integration of digital fabrication in education targets to provide experiences with innovative processes during research tasks.

To demonstrate for example the properties of surfaces that are developable, in addition to the offset operations volumetrically sculpting them in tridimensional space, it is possible to use procedures such as the flank milling. This digital fabrication procedure is defined as an advanced production approach. The use of the tip of the tool while machining is instead modified by the side of the cutter which is used in an unconventional manner by touching the surface and removing the stock in front of it. (Li et al., 2007) Surfaces can therefore be cut with a single tool path instead of using the less efficient standard point milling methods and continuously having the tool passing over the surface. It is arguable that this procedure can limit the fluidity and complexity level of surfaces. However, in some cases the use of the tool path length can considerably reduce fabrication time of rationally designed architectural components.

The double twisted helicoidal columns designed by Antoni Gaudí for the Basilica of the Sagrada Família provided a great challenge to the engineers and architects to both design and build them. (Bonet, 2001) These rationally complex geometrical elements are one example that provided the possibility of experimenting fabrication processes similar to the flank milling in architecture. However, instead of just rotating the tool to mill the object, the component itself was positioned in pivots in order to accelerate the formation of the ruled surfaces in addition to their constantly and progressively modified intersections (Fig.2).

Fig.2 Horizontal pivot numerically controlled and machine specially adapted for the fabrication of a stone component of multiple ruled surfaces for the Basilica of the Sagrada Família

The efficiency of flank milling provides interesting possibilities for exploration in architectural education, especially due to the fact that many projects require a time optimization to be produced. (Brell-Cokcan et al., 2009) Students are usually requested during digital modeling courses to design intelligent surfaces, carefully considering the geometrical properties of the design before being translated to the automated flank milling. In a simplified vectorial description, two curves can represent the flank milling tridimensional positioning of tool paths. This will be translated to the movement where the tooltip would follow for example the lower curve, while the upper curve would tilt and guide the tool axis angle.

Ruled surfaces are the common geometrical results that allow tool axis to follow families of straight lines within the surface (Fig. 3). However, this level does not properly assume the physical properties of tools to be considered in the physical work environment. For instance, drill bits attached to the router do not have a zero diameter. Therefore, as soon as the tool is defined, a diameter is requested, and therefore an offset to the final ruled or developable surface result should be created in at least one side.

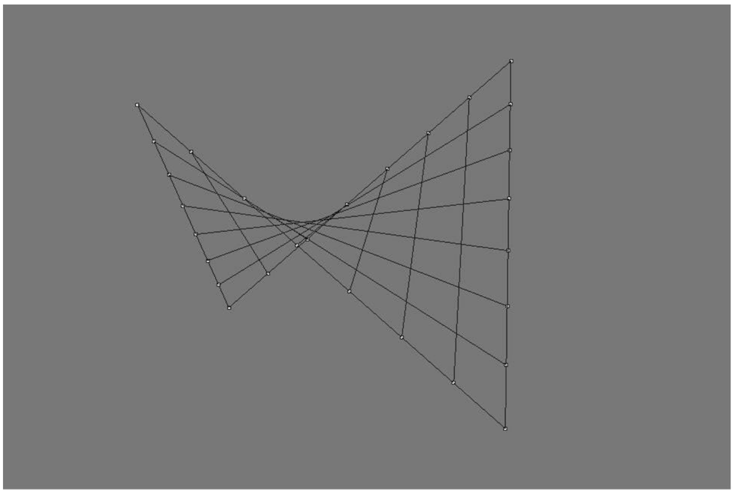

Fig. 3 Basic example of a ruled surface defined by straight lines and generating a parabolic surface

In an attempt to create an efficient, free form surface using EPS, tests were made with the intention of splitting a volume with a cutting surface in order to test if pieces would perfectly fit once stacked on top of each other. However, after fabrication, it has been noticed that parts did not perfectly fit. The object into question, if at real scale, would provide substantial deviations between the resulting edge curves as an outcome. It has been noticed that by the angle change of the tool, its diameter cross-section also changes from the top view. This is the result of the tool behavior that has to be taken into consideration. Inconstant unforeseen transitional movements are commonly realized by tool paths as procedures that are hard to control since the aim of the fabrication is focused on the perfection of the surface (Fig. 4).

However, and according to the surfaces' transitional fluidity, it is possible to solve this problem by milling along the surface in a tangential way. Even though this is not the ideal solution, and unless the target surface is geometrically developable, results can be fabricated within architecturally acceptable tolerances. This method of production can be instructed within the frame of material operability during design processes, where it is important to find the balance between geometrical properties of surfaces and their offset conditions related to how developable surfaces can be. Such method can for instance provide guides to strategies related different fabrication procedures using diversified materials such as the metallic façades of Frank Gehry's Guggenheim Museum. (Shelden, 2002) Another example that also uses EPS as the base material but a distinct tool for fabrication is the wire-cut using EPS-formwork of ruled surfaces for concrete. (Feringa and Sondergaard, 2012)

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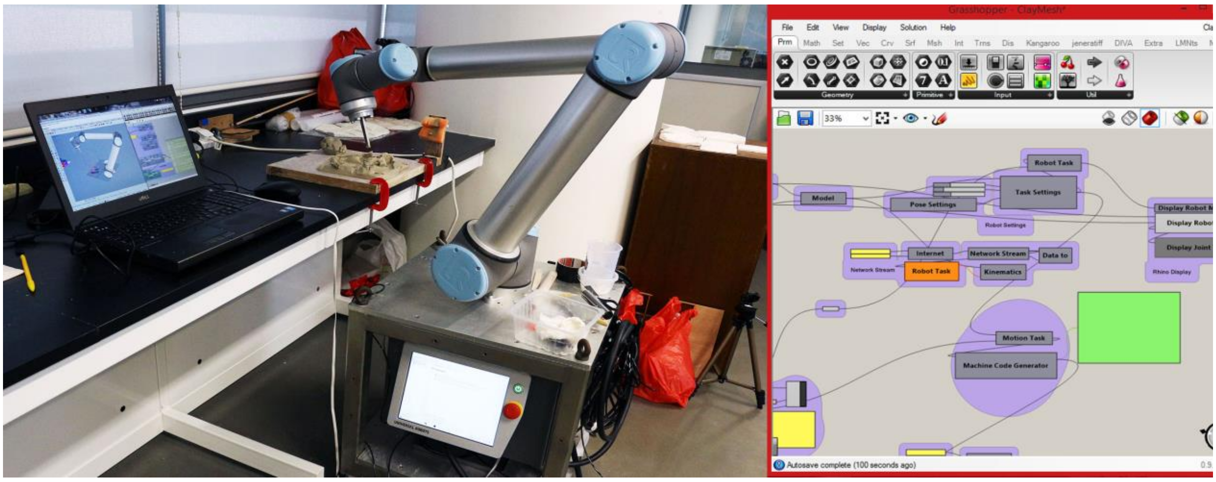

Fig. 4 Robot programming and control interface based for small scale flank milling fabrication

In fabrication complex systems related to constraints on degrees of freedom, robotic arms can be potential tools for providing pedagogical procedures. Basically, there is a great degree of complexity both at the academic and professional levels to explain advanced machinic processes when relating vectorial data at the design level with the actual tool paths needed to fabricate components. The machine kinematic movement complexity is even harder to be grasped by students as compared to the advanced digital modeling strategies that provide clearer performance visions while simulating.

Concerning digital fabrication tools and systems, when taking into consideration a robotic arm, its articulation degrees of freedom can be enhanced by more complexity, depending on the tools that are added to it. For instance, the six axial movements of a robotic arm provide it with a relatively important amount of freedom when defining objects in tridimensional ways. However, complementary movements can be enhanced by additional external axes with linear rails, turntables and cooperating robots. These extra implementations to the basic robotic arm can provide them levels of freedom impossible to attain with regular CNC machines of three or even five axis. These implemented tools can provide degrees of freedom that can play an important role in architectural education, since they have the potential to provide students with clear robotic kinematics that is able to simulate unpredictable machinic movements.

When someone is requested to move his arm from one point to another in the most efficient manner, he or she will most probably move it in a straight line. A robotic arm will in contrast select the movement requiring the least axial rotation amount, which hardly ever results in straight lines. This is a logical industrial behavior even though it is hard to predict the robot's path, especially when dealing with complex formal outcomes. This is the intuitive human thinking and mathematical lack of overlap that should be understood in such vital concepts.

3 ADVANCED INTERFACES IN ARCHITECTURAL EDUCATION

As advanced architectural design is getting to higher levels of complexity, principles of digital design and modeling are forcefully being connected to programming as a way to attain proper outcomes linked to aesthetics, materiality, and sometimes construction principles. Digital platforms such as Grasshopper are enabling students and professionals to use visual programming to define geometrical algorithms of wide complexities and to automatically apply them on surfaces and added geometries in a user friendly environment, with the possibility of results being directly linked to digital fabrication tools.

When dealing with programming interfaces, it is clearly noticed that the dependence of Computer aided Manufacturing (CAM) on fabrication strategies that are predetermined prompted designers to develop their own software tools for robots. For instance, KUKA Parametric Robot Control (KUKA|prc) was developed to deal with the visual programming environment of Grasshopper. Such software provides the possibility to visualize, robotic kinematic simulations in an accurate manner, in addition to providing native robotic code conversion commands to be directly executed by the robot. (Braumann and Brell-Cokcan, 2011) Students are provided with situations that allow greater exploration of architectural design issues instead of spending time and effort learning programming in environments that do not conform to some architectural criteria, including functionality and structural consistency. For instance, students have been involved recently in developing designs with digital tools of increasing popularity such as Rhino for modeling forms and basic relations to attain complex forms, simultaneously with Grasshopper in order to define parametric architectural design strategies in a rational manner.

Besides providing a certain order in the process of integrating digital design and fabrication to the academic curriculum, the development of these tools had offered some degree of freedom and consistency in teaching, as tasks have been able to be defined with less dependency on conventional digital fabrication methodologies. Students are able to be tasked to create their own parametric relations within a design process, allowing them to deal with issues regarding design consistency, creativity, and optimization, among others, taking into consideration the robotic possibilities and constraints to concretize their ideas through detailed fabrication simulations. Despite the arguable the fact that architects do not necessarily need in depth skills of CAM interfaces, design experimentations using parametric approaches linked to automated processes of construction are becoming a desired field of exploration in architecture.

An additional aspect that becomes relevant robotics applied in architecture is the development of complex processes. It is of vital importance for architects to be aware of the sequences during a robotic fabrication procedure. In contrast with instructions given to humans that could be somehow vague, the communication procedure with a machine should be sometimes composed of an extreme amount of actions. For instance, a simple pick-and-place operation given to a robotic arm in order to pick objects from a specific place and place them somewhere else consists of commands that require the tool to move into safety distance above the object, then to move down, to close the gripper, to move up to safety plane, to displace towards the target position, to move down, to open gripper, and finally to release it (Fig. 5).

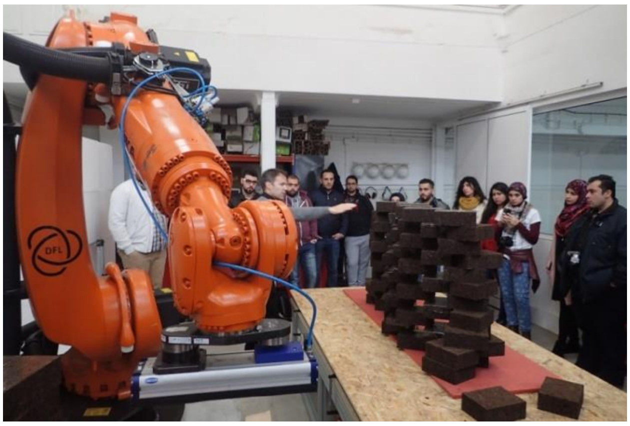

Fig. 5 A pick and place experiment carried out with students that shows the considerable amount of procedures needed for the robotic arm to perform the job

What digital fabrication technology has set as a new challenge in architectural education is the improvement of techniques for 3D printing using robotic arms in real building construction settings. Experiments and some level of success have been noticed, with companies even trying to certify their experiments in order to enter the commercial market. For instance, in robotics trade fairs, it is very hard until now to find technologies ready to print concrete using robotic arms. The solution meanwhile is to either abide by professional developers dealing with such technologies or by a multidisciplinary cooperation at the academic level in order to develop the tools and materials. As an example of the many companies struggling to implement their technologies on the market, CyBe Construction is at the final steps to release a printable concrete mix in anticipation of a 3 meter reach concrete 3D printer. The firm has come up with a material solution based on a quickly drying cement product in order to be printed as free forms or parametrically designed shapes without the need for frames or support systems, in addition to a reduced CO_2 production when printed compared to traditional concrete laying process (Fig. 6).

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Fig. 6 Examples of freeform structures printed in concrete using a robotic arm successfully executed in 2015 and under further development

An area of research of the robotic programming trend that is nowadays highly relevant to automated fabrication in general, in addition to its implications in architecture, is the development of new interfaces. Developed and under development interfaces are providing possibilities to students and researchers to interact with advanced machines such as robotic arms with more user friendly environments and less control panel interface complexities. A spontaneous sense of robotic fabrication should be acquired by students at the beginning of an educational course related to such issues. Virtual reality can help in achieving it, even though a better efficiency is reached with real performances. Frequently created by using common electronic entertainment approaches, developed interfaces as a touch-based user interface for instance allow simultaneous robot's position adjustment showing the robot in 3D directly on the screen. Interfaces related to kinetic based trajectory teaching for industrial robots have likewise been tested by many educational institutions using Microsoft Kinect motion capture device, allowing humans' body movements to interact with a robot (Fig. 7). Such interface has the potential in the future to allow people of different ages and professional backgrounds, and with no need of in-depth knowledge of automated processes, to work together with industrial robots. (Petereit et al., 2012)

Fig. 7 Microsoft Kinect is used to program a simple trajectory in an ABB industrial robot

4. CUSTOMIZATION AND AFFORDABILITY OF FABRICATION TOOLS

Custom digital tools are providing opportunities for students and researchers to go beyond standard processes of fabrication. Milling procedures for example are being transformed and redefined by the creating of new parametric fabrication strategies according to the contemporary challenges posed by the architectural context. However, applying these strategies and translating them from the virtual environment to effectively physical prototyped customs is extremely required.

The development and integration of robotic tools needed to execute fabrication tasks can usually be more challenging and expensive than the robotic arm itself. As production intentions are defined throughout architectural approaches, the design and integration of custom tools for robotic procedures has to be converted to an essential part of courses related to robotics in collaboration with other faculties such as the mechanical engineering. The resulting output varies in complexity according to materials in question. Gripping devices, milling spindles, and extruders for 3D printing attached to other tools such as cameras and laser pointers are examples of tools that need customized adaptation constantly being developed by industries. However, they can also be developed by academic institutions involved in or with interest in becoming part of this high tech revolution.

Matters that also need custom electronics such as the integration of switchable grippers or spray guns to glue bricks or pour clay are highly demanded to develop a better application of robotics in architecture. The electrical engineering field has the potential to provide solutions for such concerns. However, the merging of standardized microcontrollers from platforms such as Arduino with manageable softwares for programming languages can provide students with a proper environment to develop their own strategies, allowing the translation of instructions from the parametrically designed procedures to the robot itself.

5. CONCLUSIONS

In a struggle to merge design with fabrication within the digital spectrum, it is clear that the use of robotics in architecture has shown progressive developments. Learning to deal with environments that were out of the architectural context such as automated machinic constraints is a long process that started since the first intentions to use a Numeric control machines to build an architectural components, and is still under investigation in robotics as the challenges to fully integrate automation in architecture increase. As of today, there is no doubt that the amount of students and researches interested in robotics applied to architecture has incremented, with the idea of not just using standard tools and solutions developed by industries, but also designing their own solutions that can go beyond the borders of the conventional CNC use.

For educators, it is of crucial impact being involved in the advancements and processes of developing robotic technologies for the service of architecture instead of being more passive as merely users. This has created great dynamism in the development of robotic methodologies with potential to expand boundaries in creativity and productivity. With the proper tools and strategies, students can create any aesthetic output using robotic fabrication as long as they are able to merge their intentions with the automated system constraints. The goal is now to use industrial robots with the appropriate tools as open design interfaces.

In digital modeling courses, the properties of geometric entities such as coordinate systems and ruled surfaces should be first explained in a mathematical way before being applied in parametric design and programming softwares such as Grasshopper for robotic fabrication. Such procedures lead to real digital-physical challenges where students should deal with strategies to be applied on an automated fabrication environment. The robot in this case serves as motivator and proof of concept, which can be somehow similarly compared to the responsibilities of the professional practice conditions when architect are requested to design and build, assuming therefore the consequences of the project.

It is arguable that industrial robots have the potential to play an important role in different areas of the architectural academic curriculum, as their multiple possible functionalities allow them to be used in unprecedented ways when being compared to the traditional CNC fabrication scope. Be them of either small or industrial sizes, robotic arms can be programmed in similar ways to both produce small scale models and real scale prototypes.

Automated processes are increasingly becoming a trend capable of affecting architecture both at the educational and professional practice levels. As procedures for programming are becoming easier and more practical, robotics are having greater chances of becoming an open interface that is able deal with digital tools in order to transfer virtual data into realistic elements of architectural values. Geometric rationalization and programming are playing an important role in the digital culture of the discipline, without a previous in-depth knowledge of CAM processes. As the popularity of robotic arms applied in the construction industry is increasing, so does the probability of future practitioners to deal with robotic fabrication. And with the already developed, current and future interfaces, the boundaries of architectural design education with industrial robots will probably expand.

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