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Craft-based methods for robotic fabrication: a shift in Architectural Education

Métodos artesanales en la fabricación robótica: una evolución en la experiencia docente

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Abstract

This article discusses robotic fabrication as a tool, beyond an innovative mode of production, to reinterpret the traditional methodology of craftsmanship, such as painting or stereotomy, offering new design potentials applied in architecture. A theoretical framework is developed, comprising an approach to the role of craft; the contemporary paradigm between making and digital tools; and the context of robotic fabrication in Architecture schools. This paper analyzes the methodology and content of a series of educational and research projects (2019-2021) in which robotic fabrication has been implemented through craftsmanship methodology. Finally, these are presented as case studies, illustrating the proposed framework, and help determine its applicability, impact and limitations in a border sense, to establish a more profound dialogue between digital and material design, and demonstrate a new exploratory way of tackling Design in Architecture education.

Keywords: *active methodology, design/build, manufacturing-driven design, material exploration, robotic fabrication.*

Thematic areas: *tecnología (construcción, estructuras e instalaciones), metodologías activas (MA), fabricación digital.*

Resumen

El artículo analiza cómo la fabricación robótica, más allá de ser un innovador modo de producción, puede reinterpretar el método artesanal, como la pintura o la estereotomía, ofreciendo así una nueva herramienta de diseño en la experiencia docente. Inicialmente, se presenta un marco teórico compuesto por: el rol de la artesanía; el paradigma entre fabricación y herramientas digitales; y el uso de la fabricación robótica, en la escuela de Arquitectura. Concretamente, se analiza la metodología y contenido de una serie de proyectos educativos y de investigación (2019-2021) en los que se ha implementado el método artesanal en la fabricación robótica. Estos ejemplos ilustran el marco propuesto y ayudan a determinar su aplicabilidad, impacto y limitaciones para establecer un diálogo más profundo entre el diseño digital y material, y así demostrar una nueva forma exploratoria de abordar el diseño en la escuela de Arquitectura.

Palabras clave: *metodología activa, diseño/construcción, diseño conducido por sistemas de producción, exploración material, fabricación robótica.*

Bloques temáticos: *tecnología (construcción, estructuras e instalaciones), metodologías activas (MA), fabricación digital.*

Introduction

Robotics has opened up new avenues of designing, making, assembling and indeed the whole spectrum of architectural production. Although robots, particularly industrial robots, have been around since the 1960s, have not yet been directly linked to the design process. Furthermore, robotic fabrication establishes a new mode of production embodying different forms of material engagement which can convey a new way of thinking and design. Therefore, the use of technology as a new tool to implement in the design methodology, rather than a replacement of the human work, becomes ever more present. Building in this context, and looking towards the exploration of its ability, we can observe that the operational methodology of the craftsmanship establishes a similar relationship between production and material which can lead us to envision a great potential in its implementation through robotic fabrication. It is in this way that we are witnessing a robotic revolution that extends beyond industrial production plants and into pedagogical methodology in the School of Architecture.

The paper is structured in four parts as follows: First, it describes a historical and operational overview of the role of craftsmanship and robotic fabrication in Architecture Education. Secondly, the paper identifies key factors supporting the implementation of different craft techniques through robotic fabrication in a series of experiments developed in different educational programs. Thirdly, the paper describes the methods and metrics that were developed into these two researches after analyzing the different operations. These studies resulted in computational strategies for simplifying the different movements of each craft technique into extractable fundamental operations that can be transferred to the robot. Lastly, the paper concludes by discussing the applicability and limitations of the proposed framework, outlines opportunities for further work and potential impacts, and summarises the key contributions of the study.

1. Background: The role of the Craftsmanship in Architecture and Industrial robots

Ancient philosophers, such as Aristotle, dwelled on the nature of craftsmanship and produced various works on the relationship of theoretical knowledge(episteme) and craftwork (techne)[1]. This separation is still very present in contemporary architecture.

Building in this context, the traditional craftsman had thorough control over his tools. However, this close relationship was challenged during the Industrial Revolution as machines began to be substituted for the tools of workers, albeit only in some countries (Picon, 2013).

Twentieth-century modernists drastically separated the domain of craftsmanship from that of architecture. Architects conceived the craftsmanship work as highly interested in ornament, always closely related to the history of style. The interest in the activity of the craftsmanship within architecture was displaced by the introduction of the machine and, thus, the alignment of the craft tools, towards mass production enabled the idea of standardization in design.

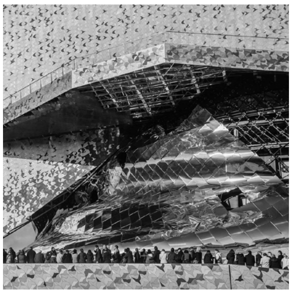
1.1. Recovering Lost Craft Tools

In 1927, Wright established the following key tenet about the relationship between the architect and the machine: “The machine is the architect's tool - whether he likes it or not. Unless he

[1]On the relationship of episteme and techne in ancient philosophy, see Plato, Protagoras (380 BC), Euthydemus (380 BC), Gorgias (380 BC), The Republic (380 BC), Timaeus (360 BC), Sophist (360 BC); Xenophon, Memorabilia (371 BC), Oeconomicus (362 BC), Aristotle, Nicomachean Ethics (350 BC), Metaphysics (350 BC); Cicero, On the Ends of Good and Evil (45 BC); Plotinus, Enneads (250 AD).

masters it, the machine has mastered him"[2] Wright argues that there must be an acceptance of the machine (technology) with the working environment of an architect or craftsperson. However, there is a clear message of using that particular machine as a tool and not having the tool dictate the architectural process.

During the last two decades, we have observed a ‘building boom’, usually related to a ‘spectacular architecture’, that caused so many off-plan investors to lose their money. As an example, in Spain between 2000 and 2008, around five million constructions were built. Seven years later, estimates suggest there are at least three million properties standing empty or even unfinished. Based on the "Guggenheim effect", a number of investigations highlight as a reason for this, the mismanagement of funds for construction as well as the failed attempt by architects in using novel tectonic solutions. It is because of this, that the construction budgets were frequently increased consistently, or even leading the building construction to ruins, post-stoppage in the development of the works, due to the inability in their execution (Fig 1-2)



Bearing in mind this context, investigation on new production systems in the contemporary industry and the implantation of them into the design method belong ever more present in Architecture. In this regard, it is of interest to mention here, the work of the architects Jean Philippe Vassal and Anne Lacaton awarded recently with the Pritzker prize in 2021, who stand out for their work with sustainable materials, as well as the recently awarded as one of the 100 most influential people of 2021, by Time magazine, the architect Kengo Kuma. Both of them have demonstrated the benefits of using efficient and sustainable construction strategies, working with local traditional materials and production systems.

[2] John Ruskin and William Morris turned away from the machine and all it represented in modern art and craft. Perhaps, Frank-Lloyd-Wright expressed his desire to reaffirm and expand the role of the architect as a matter builder by challenging Leon Battista Alberti division between design concept and building. To see, Wright, F. Ll., In the Cause of Architecture (March, 1908) This approach is also interesting in the article by Iain Maxwell and Dave Pigram: In the Cause of Architecture: Traversing Design and Making. (Anyone Corporation. No. 25, 2012) pp. 31-40

In this connection, today we find ourselves looking at the midst of a significant transformation regarding the way we produce products thanks to the digitization of manufacturing. This transition is so compelling that it is being called Industry 4.0 to represent the fourth revolution that has occurred in manufacturing. The fourth industrial revolution takes what was started in the third with the adoption of computers and automation and enhances it with smart and autonomous systems fueled by (Big) data and machine learning.

This approach to computers and automation relies on the recent advances in generative and algorithmic "bottom-up" design that have produced a new relationship between form and production, which leads to a more accessible and sophisticated methodology. As a result of all this, to further develop applications of these innovations, the notion of a univocal synergy between technology and design in Architecture education has appeared as an urgency. From the educational scenario, we can see the emergence of the exploration of the potential of these applications and their innovative aspects by developing a reciprocal learning methodology between machine and design (open-ended process)

In this connection, over the past decades, the rise of decentralized open-access laboratories available to design professionals, induced by rapid prototyping, provides us with broad accessibility to tools, manufacturing methods and material limitation systems to optimise our production patterns. This has created a culture based on the logic of Production-Material. Hence, the role of the architect changes and an experimental approach to materializing architecture is facilitated. This development has allowed professionals, who formerly focussed exclusively on design iteration, to gain a practical understanding and create various manufacturing-driven design processes as one agency, bringing the digital forms closer to their materiality with the help of CAD-CAM processes.

Building on this context, technology moved forward from mechanization to digitization (Deniz Balık & Açalya Allmer, 2017) By means of technology, ornament and craftwork today has become an important way of experimenting with form, structure and surface. Thanks to the current accessibility to tools and manufacturing methods, the re-emerge use of craft tools through the use of novel digital tools is ever more pertinent, finally towards material engagement strategies in construction and the development of sustainable architecture.

1.2. A heuristic approach to craftsmanship through digital tools

Within education, and in relation to architecture school, from the Bauhaus manifesto (Gropius 1919) to the latest Howard Risatti analysis (Risatti 2013) we can observe how artisanal processes have traditionally been conceived as a source of ornamental, figurative or historical inspiration.

In contrast to this view, this paper addresses craftsmanship as an open-ended development methodology that establishes a continuous negotiation between the process of making and the material outcome. This approach includes the investigation of aspects such as material properties, production and representation, as well as emerging tectonics and the continuous interaction between technique and machine.

David Pye (1968) defined the basic principles of craftsmanship through "certainty" and "risk", as two main poles of the operational methodology, with regards to the spectrum of emerging possibilities of involvement with the material, where risk is managed through the skills and abilities of the craftsman in anticipation of unexpected results. Thereby, the methodology of the artisanal process is usually associated with specific parameters such as "singularity" or "uniqueness" as well as normally related to highly qualified work, exclusivity, and often comes at high costs. In contrast to this line of thought, contemporary digital tools and manufacturing systems can easily be parametrically defined, as well as variated accordingly depending on the material outcome, therefore maintaining the aspect of exclusivity while offering a higher level of accessibility.

Another important aspect with regards to the craft methodology is the interaction of Artisan-Material, which requires continuous synergy between Production-Outcome. To this end, Richard Sennett (2008) considers that "Making is thinking". Furthermore, Mario Carpo(2017) refers to today's digital architecture with a nuanced approach describing the use of digital tools beyond just being new ways of making, but rather a ‘brand new science’ which in ‘its own way’ provides us with a new way of thinking. This emergent notion of ‘digital materiality’ was theorized in depth by Leach, Turnbull and Williams, and there is a close link between digital technologies and their impact on new modes of digital craft production as a fundamental component of the new tectonic languages in architecture (Veliz, Jabi, Gomaa, Chatzivasileiadi, Ahmad, Wardhana, 2019)

Building on this framework, the current affordability, immediacy and accessibility to robotic programming and fabrication resources (S Brell-Cokcan, J Braumann, 2013) gives us - designers - the possibility to implement a flexible system that holds variation through a multifaceted methodology composed of constant iteration, discovery and material negotiation. This framework, therefore, provides an accessible path to what we understand as the operational methodology of craft practices, thanks to robotic fabrication, where the craftsman engages with material in an open-ended negotiation resulting in anticipated, yet unexpected results. Thus, creating a new way to evaluate and work from controlled ‘material coincidence’.

1.3. Industrial Robots in Architecture Education

Beyond commercialised systems and proven applications, the advent of robotics in Architecture education dates around 2005. Robot whisperers, architects, engineers and networks of roboticists (such as the Association of Robotics in Architecture) emerged as the pioneers of the new era of robotics in architecture. Take, for instance, the pioneering work by Fabio Gramazio and Matthias Kohler at ETH Zurich, the Institute for Computational Design at the University of Stuttgart and the Master in Advanced construction and Robotics at the Institute of Advanced Architecture of Catalonia - IAAC-.

Moving beyond digital fabrication, through these examples among others, we can observe how digital technology and robotic fabrication contributes to contemporary architecture as a tool to design and expand even further, allowing for an exponential shift in scale, as well as the blurring between the processes of production and design within architecture education.

Recent projects and reports on robotic fabrication in architecture have extensively referenced craft as a mode of production embodying different forms of material engagement. This can be witnessed in research and projects realized through the use of robots to cut a large array of mass customized masonry units by exploring the stereotomy technique (i.e. “Periscope”, by Matter Design, 2010; and Fabrication Based Design and RhinoVault, Feringa, Hyperbody TU Delft, EZCT Architecture & Design Research, 2012); the use of robots for clay deposition developed by the Harvard GSD Design Robotics Group as a means of fabricating woven architectural panels exploring traditional coiling techniques(Friedman, Kim, Mesa, 2014); the use of robots to develop a dip-forming process achieving the crystal-clear effect of the glass craft technique at the National Chiao Tung University (Chi-li cheng, June-hao, 2019); the use of robots to translate a traditional sand carving technique for rapidly carving to create free-form and architecturally scalable unique volumetric elements (Kalo, Tracy, Tam, 2020); the use of robot provided with a bandsaw to cut a series of curved strips by exploring traditional woodcraft within the constraints of live-edge wood flitches developed at IAAC[3]; or even to use robots to quickly and easily assemble complex timber modules, refined through an algorithm which continually recalculates their path, created within the Gramazio Kohler Research, ETH Zurich and ERNE AG Holzbau[4]

Gramazio and Kohler (2008) explain that fabrication and digital production allow architects to engage directly with notions of traditional tectonics through digital means. Hence, robotic fabrication stands out as a particularly transdisciplinary technology. Therefore, the capacity to inextricably link design and production within a single environment belongs ever more present in the school of Architecture.

In consequence, robotic fabrication aligns with pervasive and key definitions of craft, despite being developed within institutionalized professional and research frameworks of practice. The following chapters illustrate how the two research projects presented here have acknowledged and followed this approach to craft studies.

2. Craftsmanship operation methodology and Robotic implementation

Bearing on this context, the different exercises here analysed were developed through hands-on experience on robotic systems, in which parameters such as angle deposition of material, speed movement, material drying time, among others were studied carefully through physical and digital tools. The goal of this work was to teach students how to deal with a six-axis machine with offline programming. In addition, and in relation to an educational environment, getting hands-on experience on these technologies and new ways of using them, will help in fostering knowledge and dissemination of these advanced tools.

2.1. Craftsmanship: Understanding a form of work

To understand the procedure of the exercises here analysed, a methodology of ‘pure craft’ is presented which will be then followed on the implementation into the robotic context, and finally, used to analyse the completion of the results. These traits are used as reifications of a 'pure craft' concept, a way of working that is the apogee of manual work. The traits of pure craft are[5]:

(1) Working and problem-solving.
(2) A hand-tool-material relationship.
(3) Work is a negotiation with materials rather than dominance.
(4) Work activity is haptic, physical and dextrous.
(5) Judgements of completion are tacit, lack codification and are based on the values of the craftsman.
(6) Work practice is based on a long period of training and the worker is within a field of established norms of behaviour. There is practised expertise.

[3]Bandsawn curved lumber is a project of IaaC, Institute for Advanced Architecture of Catalonia developed at Master in Robotics and Advanced Construction (M.R.A.C.) in 2018 by students: Filip Biliecki, Jean Nicolas Dackiw, Soroush Garivani, Sujay Kumarji. Faculty: Dir. Alexandre Dubor, Raimund Krenmuller, Kunaljit Singh Chadha.

[4]Spatial Timber Assemblies is a joint collaboration of Gramazio Kohler Research, ETH Zürich and ERNE AG Holzbau. Zurich, 2016-2018.

[5]The traits of this methodology belong to a way of understanding the craft procedure with stone. These traits have been extracted from a paper related to house building in the UK that relied on traditional and overtly manual methods: Brett, R. , Thomson, D. and Dainty, A.. Coping with stone: a short-term ethnography of skilled work in uk housebuilding (School of Architecture, Building and Civil Engineering, Loughborough University, Epinal Way, Loughborough, Leicestershire LE11 3TU, UK)

(7) There is creativity and uncertainty of outcomes until the end.

Following these traits, the paper analyzes the methodology and content of a series of educational and research projects developed between 2019-2021 which include the implementation of different craft techniques through robotic fabrication, such as painting and stereotomy.

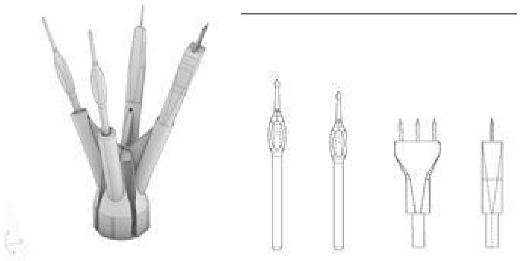
Firstly, this study follows intense two-week workshop research aimed at translating traditional Ebru Art into a new robotic enabled framework for rapidly painting on a pan of oily water and then transforming this pattern to a special paper. Secondly, it presents a 6-week seminar to explore the art and science of cutting three-dimensional stone solids (stereotomy) via the use of robotic fabrication transforming the diamond wire for stone into hotwire for Expanded Polystyrene (EPS) to develop an architectural system.

2.2. Background of the traditional craft method: Analysis, Material and Tools preparation.

The first case study explores the Ebru Art painting, traditional Turkish and Central Asia art, which creates colourful patterns by sprinkling and brushing colour pigments on a pan of oily-water base and then transforming this pattern to a special paper. This technique is also known as paper marbling.

First, the artist mixes water with pigment and natural gum, to produce a dye that won't be dissolvable into the oily-water based. Secondly, the dyes are sprinkled to the surface of the size through a set of unique tools such as bristled brushes, or even, the fingers or tiny food such as nuts, seeds, or matchsticks. Thirdly, an awl is used to manipulate the colours into designs and patterns. Once the artist has completed this one-of-a-kind “painting” process, a sheet of special paper is carefully placed on top of the size in order to transfer the image.

Building on this methodology, towards the implementation into the robotic fabrication, the end effector is the tool that does the work of the robot. An end effector with multi-devices is mounted on it to make a robotically drawn composition. This tool is developed through 3d printing technique and is composed of four-finger inputs which would be later provided with a thin brush, a fatter brush, and two types of awls (Fig. 5)



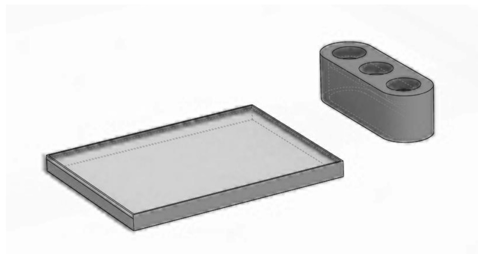


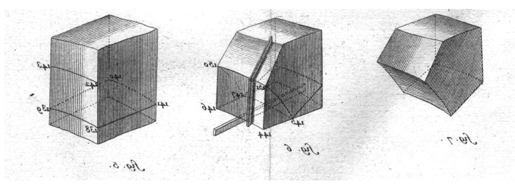
Fig. 5 Multi-device tool[6]: thin brush, fat brush, awl type1 and awl type 2
Fig. 6. Oily-Water based canvas + Dye recipients

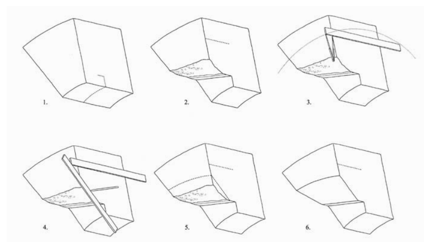
The surface of the canvas base is 215x285 mm developed through transparent acrylic of 4mm thickness cut through laser cutting technique (Fig. 6). Last, a wood base is created to place the final drawing drying after the composition is taken. During this process, the dyes dry into the paper extracting all the water from the drawing.

The second case study here presented, explores the art and science of cutting three-dimensional stone solids (stereotomy) through wire cutting which is an important technique for reducing production time and increasing the quality of elements realization.

In contrast to the first case study, several projects through robotic wire cutting were previously developed with qualified and complex results (i.e. Matter Design, 2010; Odico, Hyperbody, McGee, 2012; Feringa, Hyperbody TU Delft, EZCT Architecture & Design Research, 2012) In this paper, craft technique of cutting stone is framed through the application of the crafting procedure and helps determine its applicability and benefits of the implementation into the robotic context.

Over this connection, there has been a growing interest in material processes that can support an architecture of volume, investigating materials that are unconstrained by the limitations of sheet-based materials (McGee, Feringa, Søndergaard, 2012) The first essays on stone cutting were written in the XVI. It is through the essays of Gelabert and De la Rue[7] that we can find the first explanations and drawings of traditional stone masonry (Fig. 7-8). It means the description of the cutting process of a piece starting from a simply roughed block.





[6]This tool was previously designed by Kunaljit Chadha for the project Robot Orchestra, done by IAAC in collaboration with Ceramica Cumella, in 2019. Later, the tool was modified and adjusted accordingly to develop the Ebru Art technique.

[7]This conclusion is extracted through the reading of the following article: Enrique Rabasa Díaz, Traza, descripción, razón. Lenguaje y grafismo en los tratados de corte de piedras. Teoría y literatura artística en España: revisión historiográfica y estudios contemporáneos. ISBN 978-84-96406-36-0, págs. 412-459. 2015,

Building upon this groundwork, currently, we can observe mainly the following craft methodologies used for ornamental stone processing: diamond wire, primarily diamond segment discs and frame saws. A conventional stationary wire cutting machine for the processing industry weighs around six tons and has a cutting motor. The cutting tool is a steel wire, on to which diamond beads are attached (Fig. 8-9)

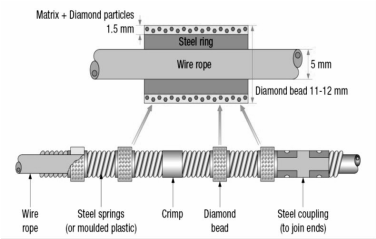
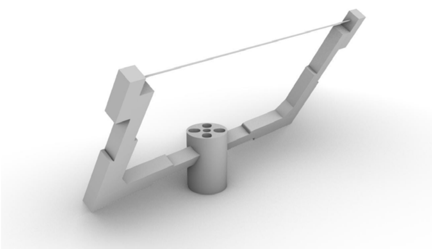


Fig. 8 Schematic view of diamond cutting wire; Fig. 9. Brown granite cutting in progress.

As previously mentioned, a number of investigations were undertaken using robotically manipulated abrasive wire cutting equipment. Likewise, developing an end effector to mount abrasive wire saws to robotic equipment for the purpose of cutting stone. The diamond cutting wire has several advantages when compared with CNC milling or multi-axis bridge saw cutting as well as semi-finishing operation results. In this paper, and within the educational environment, the implementation of the technique into the robotic context was carried out through hot wire cutting with expanded polystyrene (EPS), as a proxy for stone, which is one of the lightest and least expensive volumetric materials available.

The Hotwire cutting tool mounted on the robot consists of a thin, taut cutting wire made of nichrome wire of 0.3mm thickness which was heated via electrical resistance to approximately 500°C. to cut the EPS blocks (Fig. 10-11). At the beginning of the seminar, students were provided with the hotwire cutting tool and EPS blocks of 200x200mm and 400mm of height dimensions.



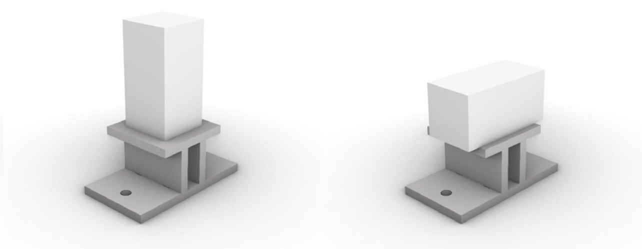


Fig. 10 Hotwire cutting end effector; Fig. 11. EPS base, different positions of the blocks.

2.3. Robotic cell and movement observations: From Handwork to Digital

The Atelier Lab at the Institute for Advanced Architecture of Catalonia - IAAC- in Barcelona includes a 6-axis ABB IRB 140 robotic arm (6kg payload, 810 mm reach, IRC5 Controller) and ABB IRB 120 (3kg payload, 580 mm reach, IRC5 Controller) utilized for both processes, EbruArt and Stereotomy wire cutting.

For this, a series of experiments have been iteratively conducted. The geometries of prototypes have been modelled in Rhinoceros® via Grasshopper's Robots® plug-in. The robotic path developed through this plug-in explores the motion-defined path to find a sequence of valid robotic configurations that moves from the source to the destination. In all the studies presented here, the robotic path was elaborated through different geometry inputs from where, lastly, a specific set of planes was extracted then sent to the robot. Each operation has been designed based on unidirectional tool paths.

In the first case study, the following operations from the craft methodology were studied carefully and translated to the robotic path: paint sparkling, drip and manipulation (Fig. 12)

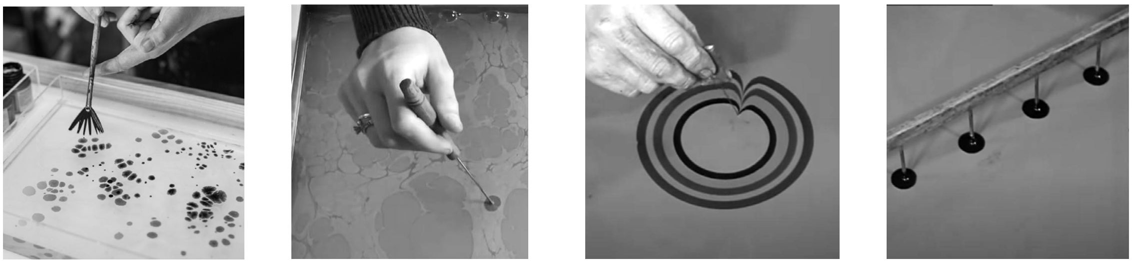


Fig. 12 Ebru Art technique operations: Sparkling, Dripping, Paint Manipulation and Multiple manipulations. Images extracted from a film made by Bedfordshire Record Office of Cockerell marbling in 1970

During the workshop, students were provided with the material and scripts to generate all operations through different tool paths from digital software to the physical machine. The first operation, sparkling a watery paint into the size, was developed through manual work establishing a first hand-tool-material relationship as well as learning how to implement both collaborative processes, manual and robotic fabrication. Secondly, students develop the dripping movement through a digital path composed of a few sets of points, as a geometry input. Sequentially, students generated different geometries through curves input with regards to the previous paint deposited into the base. This work aims to develop a paint manipulation operation into the oily-water base through two different paths: initially, a unique awl tool, and afterwards, an awl composed of multiple pins. (Fig. 13)

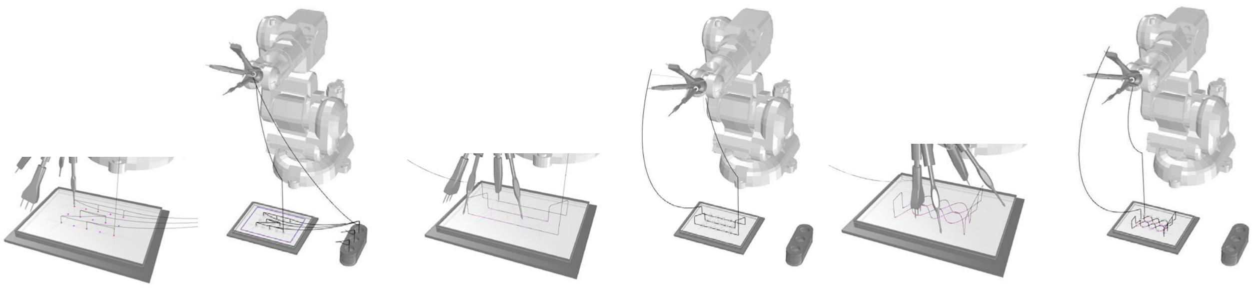
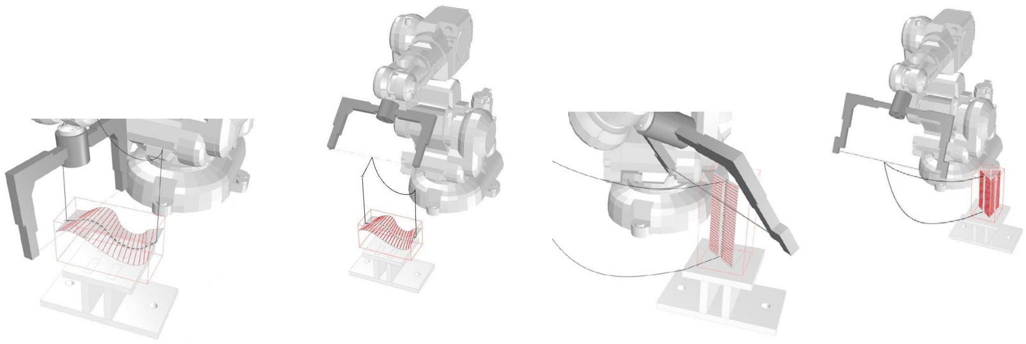


Fig. 13. Images of the robotic path programming characterization for the dripping operation, for the awl manipulation type 1, and for the awl manipulation type 2.

In the second case study here analysed, students started from studying the methodology of cutting blocks using the hot wire tool in order to implement the design constraints into the research. This technique reduced drastically the amount of milling necessary as well as rationalizing the intended shape as a piecewise ruled surface.

A ruled surface can be described as the set of points swept by a moving straight line. This means that through every point of the ruled surface there is a straight line, in this case, the path of the nichrome wire, that lies on the surface.

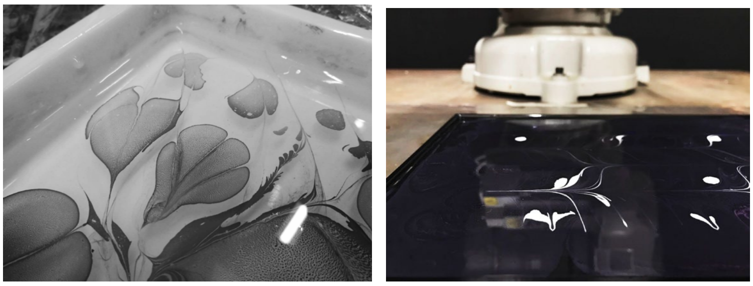


The elaborated script to develop the robotic path through the ruled surface was given to students at the beginning of the session. In this case, the geometry input is a ruled surface in which, as mentioned previously, a specific set of planes were extracted and then sent to the robot (Fig.14)

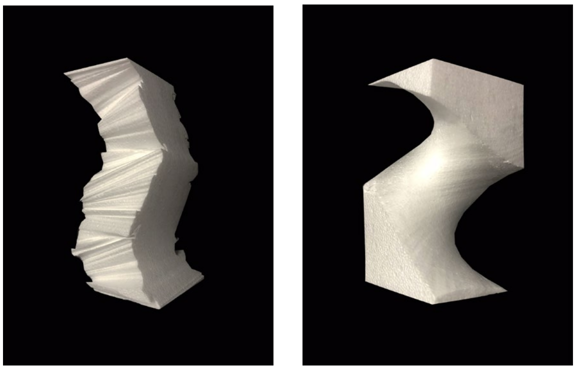
2.4. Robotic movements: corrections-re-implementation

Following the method and workflow explained above, students started to develop different negotiations with materials through the use of tools and robotic fabrication.

In the first case study, Ebru Art painting, it was observed that in order to achieve specific results the robotic movements deferred considerably that the initial studies on the digital software due to the spreading of the paint into the oily-water base (Fig. 15). A specific rule, establishing the spreading area of the paint into the oily water base, was established to further develop the work. Then, building on this rule, an approximative guideline to precisely locate the geometry input for the awl operation was implemented into the digital software.



In the second case study, during the initial tests cutting manually with the hotwire tool, students realised that the high heat temperature of the nichrome wire increases the loss of material, as well as the speed of the cutting movement, later developed by the robot, changes it significantly (Fig. 16). Then, some technique tolerances from the physical models were explored and thereupon implemented into the digital designs in order to reach specific precision results of the EPS blocks, for the subsequent combination of them.



In the same way, in order to correct the tolerances issues, students were provided with a number of methods to read the block location and then accurately implement it according to the digital path. Lastly, students explored digital tools such as performance, physical and compressive strength simulation to implement them into the design development in order to achieve desired shapes.

In both processes, different design analyses were requested and elaborated by students to identify the parts of the material outcome which were not possible to produce or implied some issues in the robotic simulation.

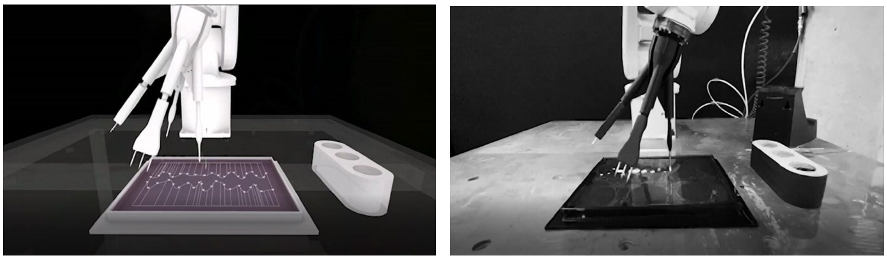
3. Research methodology and Results

3.1. Methodology

(It is important to mention here that this chapter was developed following the order of the 'pure craft' traits mentioned above)

A series of tests and robotic attempts, both successful and failed, have allowed the definition of this methodology, characterized following standard material studies through digital and physical explorations, in a constant and open-ended learning process.

In both processes, Ebru art painting and hotwire stereotomy, the first step of the methodology started from a set of manual tests (1- Working and problem solving; 2- A hand-tool-material relationship) in order to explore the hand procedure to further implement into the robotic digital path. Subsequently, a set of digital simulation exercises (3- Negotiation with materials) were carried on to analyse the correct robotic movement and development of the technique (Fig. 17).



Based on this experience, on one hand, we can observe a methodology in which every step is feeding the consequent next one. And, furthermore, thanks to digital tools and robotic fabrication, students developed several design iterations as one agency towards the brief requirements (4- Work activity is haptic, physical and dextrous)

On the second hand, this methodology establishes a procedure in which digital work and fabrication are constantly developed, establishing constant learning through the use of technology and design (6- Work practice; 7- Creativity and Uncertainty).

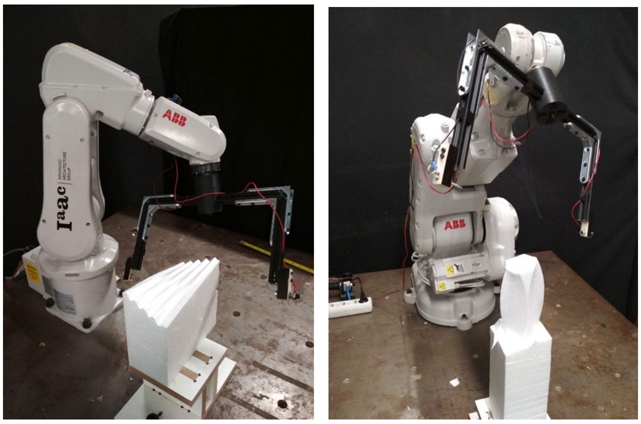
Lastly, in both processes, an initial brief requirement was given to students as well as they were distributed in groups. To achieve the specific requirements, firstly, students had the opportunity to develop a parametric system that exhibits a 'File to factory' workflow, capable of integrating fabrication constraints, robotic kinematics, assembly logic, and architectural goals.

Secondly, it was established a guideline from which was evaluated the final work (4-Judgement of completion) based on the following basis:

(1) To outline a current state of the art (craft technique framework).
(2) Analysis of the manual movement of the craft technique.
(3) Implement the manual work into the robotic fabrication.
(4) Proposes a system adjusted to the brief requirements.
(5) Conduct a scale feasibility test.
(6) Explanation of the impact and limits of the proposed system in connection to contemporary industry(technology).

3.2. Results

Following the workflow and path programming methods described above, students explored possible solutions and demonstrated a proposed system through the work with robots (Fig. 18)



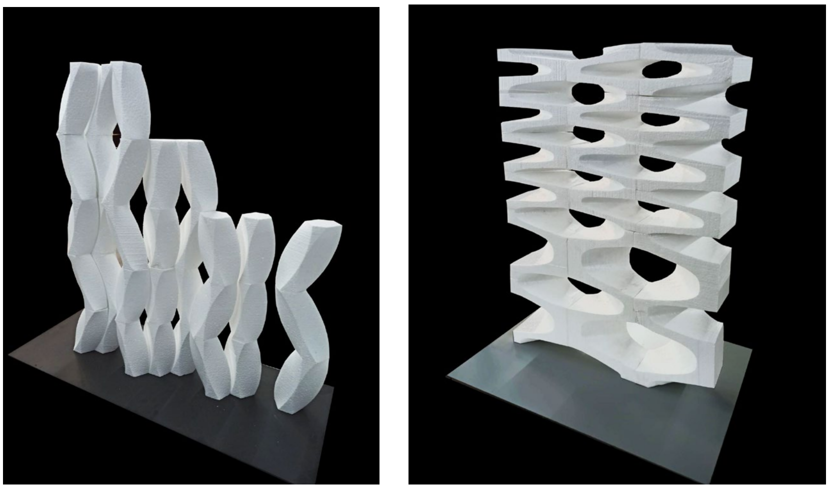
[8]

In the first case study, it was required to present a final robotically drawing composition into a dry paper together with the digital file system that integrates the robotic kinematics, fabrication constraints, operations logic, and drawing goals (Fig. 19)

[8] This work was developed in groups by the students: Group 1: Liang Mayuqi, Elizaveta Veretilnaya and Xingyu Zhang; Group 4: Alexander Dommershausen and Iulia Lichwar.

[9]

In the case of the work with the hot wire cutting technique, students proposed an architectural system adapted to the robotic manufacturing of stone elements via wire cutting equivalent to a 1:5 model (Fig. 20). The system was evaluated on the basis of efficiency (ratio of used material vs waste), stability (capacity to support self-load and external loads), lightness (ratio of empty space vs material volume) and texture (additional performance for light or strength)



[10]

3. 3. Suitability of research, objective statement and paper outline

In both cases, a constant open-ended process of discovery and negotiation, between robotic fabrication and material outcome, was observed. Likewise, the robotic fabrication (developed from the thorough studies of the craft methodology) can be parametrically defined and adjusted (S Brell-Cokcan, J Braumann, 2013) in order to control, simulate, visualize and correct before commencing the production process. This framework, therefore, provides a new method to the craft logic of Production and Material, which can therefore maintain the aspect of completion exclusivity while offering a higher level of multiple iterations.

Therefore, despite the fact that there is a control over the process that is intended and designed accordingly, there are parameters such as risk and certainty that are still open and difficult to predict until the machines go to do their job. For this reason, risk and certainty are modified from

[9]This work was developed in groups by the students: Saurabh Singla, Bharath lakshmesh, Vinay Prabhakar, Siddharth Aryamane and Aditya Ravindra Mandlik. Liang Mayuqi, Elizaveta Veretilnaya and Xingyu Zhang.

[10]This work was developed in groups by the students: Left image: Group 4: Alexander Dommershausen and Iulia Lichwar; Right image: Group 3: Shubham Dahedar, Kajal Unahariya

the specific craftsmanship capacities and skills, becoming a new territory of exploration through digital tools and material fabrication into a constant learning process between us, machine and outcome.

Building on this connection, this method requires establishing a new approach to the tools inside the design process. Accordingly, the results of this research show that it also has two levels of focus, one is for the physical layer and the second is for the digital layer. It is essential to integrate both levels on the design task in Architecture. Based on this, on one side, the design task would open the possibility to explore the digital tools and machines as a part of the process of 'editing' design. On the other hand, it defines an approach to the development and use of technologies closely linked to the idea of empowering people to make real applications of technology solutions to solve problems in the most efficient and rational way possible.

4. Conclusions

In the light of these exercises, this method generates a 'heuristic way' in which we experiment and ask questions through the exploration of Production-Outcome (Craftsman-Material) consequently, the idea of 'constant learning' and 'tacit knowledge' becomes ever more present in the pedagogical methodology.

Secondly, the use of these new tools and their implementation in the Architecture Design makes closer the relationship between education and industry, fostering knowledge and productive systems in the future of the discipline.

Existing working methods are not expected to be overridden, but rather to incorporate and facilitate socio-technological innovation on an existing material system and its associated artisanal nature. Moreover, it establishes new avenues to connect architects and technology, consolidating their integration in the contemporary industry. This approach, as a result, rely on strongly on the basis of craftsmanship (in this case, digital craftsmanship), providing a new or enhanced way to interact with materials, through an augmented path, in which professors and students, together, research by design and experimentation through the use of novel digital tools.

Over these considerations, we can observe an emergent shift in education, breaking free from the traditional separation between design and manufacturing, towards a contemporary approach in which we adopt these technologies to foster a new way of thinking in Architectural Education - design and practice.

Finally, learning from these two experiences, and based on this methodology, IAAC has explored and produced a large series of successful experiments and prototypes, applying robotic fabrication within its educational programs, consolidating an emerging paradigm within the current production system.

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The research in "Introduction to Robotics: Ebru Art painting' is a project of IAAC, Institute for Advanced Architecture of Catalonia developed at Master in Advanced Architecture (M.A.A.) in 2020 by:

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Assistant: Alaa Aldin Al Baroudi

Students: Lilett Ricaurte, Matin Darabi, Deniz Akyurek, Eve Nnaji, Alisa Iureva, Ilaena Mariam Napier, Zackary Bryson, Bruno Ganem, Sumit Nemmaniwar, Lim Chim Meng, Ahmad Albaalbaky, Teddy Fadous, Stefana zapuc, Lea Garguet-Duport, Madhavi Ojha, Osmin Avalos, Mario Sequeira, Xhilda Kulla, Michel L'eglise, Mauricio Casian, Aditya Mandlik, Siddharth Aryamane, Vinay Prabhakar,, Bharath Lakshmesh, Saurabh Singla, Harsh Vora, Frank Feng, Taras Kashko, Hunter Paine Chaitanya, Rani Kamel, Hanna Lepperod, Daniel Nahmias, Andrea Giacomo de Stasio, Nitha Shivapuram, Abhishek Sharma, Francesco Polvi, Brenda Freitas, Nihar Mehta, Dusan Savicevic, Robyn Catherine Houghton, Suyash Chandrakant Sawan,Tomas Garcia de la Huerta, Vatsal, Ibrahim Kukner, Ka Man Lee, Ines Cavar, Poojitha Tadshina Reddy, Aditya Ambare, Dinesh kumar Vellingiri, Nareh Khaloian Sarnaghi, Maria Andrea Gameros, Pratik Dhamale, Deepika Raghu, Sneha Vivek, Akshay Mhamunkar, Sai Preetham Alapati, Ashfaq Fazil, Swathi Lakshmi, Yash Palshetkar, Roshin Anthoora Valappil.

The research in "Introduction to Robotic fabrication: Exploring possible applications of Robotic Stereotomy for architecture" is a project of IaaC, Institute for Advanced Architecture of Catalonia developed at Master in Advanced Architecture (M.A.A.) in 2021 by:

Faculty: Alexandre Dubor, Ricardo Mayor Luque.

Assistant: Ilaena Mariam Napier, Madhavi Ojha.

Students: Alexander Dommershausen, Iulia Maria Lichwar, Lekha Gajbhiye, Aniket Vijay Sonawane, Shubham Dahedar, Kajal Unahariya, Liang Mayuqi, Elizaveta Veretilnaya, Xingyu Zhang.

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