Towards Robotic Fabrication in Landscape Architecture

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Abstract. With the fourth industrial revolution advancements, digital fabrication and automation have been widely adopted in design and manufacturing domains and deliver exceptional architectural design and fabrication potential. Specifically, robotic fabrication, as cutting-edge technology, pushes the boundaries of architecture to reach structural improvements. However, the potential for robotic fabrication of landscape architecture, which goes beyond the automation and maintenance of existing techniques, remains relatively untouched. This research explores the potential of robotic fabrication in landscape architecture by evaluating its applications in architecture. Therefore, a systematic review was conducted on pioneering architectural research groups involved in robotic fabrication projects. The collected projects were classified and analyzed based on their main parameters, including material, the implemented task, final products, and goals. This evaluation system helps to identify new areas of activity that will enhance landscape architecture, and it will help to change the historical link between a landscape architect and his production techniques.

Keywords: Digital Fabrication, Automation, Industry 4.0, Landscape Architecture, Robotic Fabrication.

1 Introduction

Since the turn of the 20th century, the field of robotics has attracted the public's attention. Electro-mechanical equipment controlled by a computer program or electronic circuitry is commonly thought of as a robot. Robots are frequently created to adopt human-like behaviors to provide the user with helpful labor. They are programmed to perform certain behaviors and respond to commands (Westort & Shen, 2017). Although robots are widely utilized in industry, the technologies and solutions used in robotics and automation nowadays are mostly not generic but rather domain-specific. The industries that rely on manufacturing processes in which the work pieces can be moved around a manufacturing plant have benefited most from this technology (Buchli et al., 2018). Recently, numerous design and construction disciplines have been transformed by the possibility of fabricating components directly from design information. Therefore, robotic fabrication has become a hot issue of study in architecture.

2 Literature Review

The relevant literature is addressed in two main areas. The first section presents existing research on robotic fabrication in architecture, where we provide an overview of merging robotic tools into architectural projects. Then, we emphasize the current research on various robotic applications in landscape architecture.

2.1 Robotic Fabrication in Architecture

"We become what we behold, we shape our tools, and then our tools shape us (Culkin 1967)."

The above quote by John Culkin conceptualizes the function of new digital design and robotic technologies in the architectural and building sector. Robotic fabrication is an interdisciplinary discipline focusing on the creative use and forward-thinking advancement of robots in architecture (Gramazio & Kohler, 2014). Architects use different capabilities of these tools to prototype and create complex designs that are challenging to manufacture using traditional methods. This approach opens up some new opportunities for innovative design explorations. Today, Architects with little to no scripting experience may program devices like industrial robots using specialized plug-ins for Grasshopper, such as KUKA|prc or HAL. Processes are advancing quickly, making it possible to modify and individualize architectural design and its materialization with minimal time and effort. This advancement in digital fabrication fundamentally alters how architects interact with technological devices and offers fresh insight into the interplay between the digital and physical worlds. Thanks to the development of new, robotically assisted manufacturing techniques, designing new materials and geometries with novel functionalities is now possible. This promotes a new way of thinking about architecture's process, application, and aesthetics of architecture (Weissenböck, 2015).

Furthermore, architects benefit from these robotic manufacturing technologies for construction. The construction sector has struggled with low productivity, a lack of skilled workers, and high accident rates on job sites during the previous few decades. Therefore, there is an unmatched need for automation and its possibilities as a viable solution to enhance worker safety, boost environmental sustainability, and address labor shortages and efficiency (Yu, Zhang, & Zhang, 2021). The sustainability of architectural construction is mainly improved by using naturally occurring and recycled materials.

2.2 Robotic Fabrication in Landscape Architecture

The term "landscape" describes the essential collection of components, such as landform, water, and vegetation, or a complicated interaction of dynamic forces operating across periods, from seconds to centuries (Ervin, 2003). As a result of the 19th-century development of hydraulic machinery, landscape architecture has evolved. Recent trends in landscape architecture require the discipline to embrace more expansive territorial systems, such as naturally occurring processes or performance-oriented physical events (Duque Estrada et al., 2020).

Due to the irregularity of natural terrains, they provide a high level of difficulty for digital fabrication. This circumstance is known as uncertainty in the world of robotics (Shaked & Dubin, 2019). The uncertainty is caused by differences between the virtual model and the real world, unexpected material behavior in their interaction, and problems with motion planning and control that result from these differences. An iterative robotic fabrication process can overcome these issues (Bar-Sinai et al., 2019). However, due to the intrinsic complexity of the reality on-site, robotic fabrication in landscape architecture has lagged behind other fields like architecture and infrastructure engineering (Hurkxkens, 2020).

Although the current on-site robotic construction techniques in landscape architecture aim at planning and horizontal grading through the optimization of material flow (Bock & Linner 1995) with the use of GIS guidance systems (Petschek 2014), a more sensitive approach to the local topological and material circumstances is required for landscape architecture (Hurkxkens et al., 2017).

Besides, the on-site construction techniques and materials are tied closely to environmental factors such as ground stability, severe winds, and other factors (Keating et al., 2017). Therefore, robotic landscape modeling on location needs to be flexible enough to adjust to these shifting environmental factors. For instance, in a recent study, robotic landscapes were suited to local conditions by utilizing only on-site materials, balancing cut and fill, and adapting the design to the found material (Jud et al., 2019). Alternatively, another study introduces a revolutionary coastal design strategy for autonomous construction in dynamic environments, merging several technologies to create new possibilities for design exploration and research. Instead of using conventional engineering methods to address the problem of extreme erosion in coastal environments caused by storm surges, the paper integrates robotic and natural processes into continuous maintenance strategies for dynamic coastal defense structures that concentrate on local material changes and bathymetry modification. This procedure uses erosion and sedimentation's potential for forming landforms while minimizing the mechanical intervention necessary to accomplish coastal remediation goals (Hurkxkens, Pigram, & Melsom, 2021).

Although the existing research on landscape robotics provides noteworthy developments, they are limited in quantity. We need more design research, tools, and procedures for landscape robotic fabrication today.

3 Methodology

This paper aims to find the potential of robotic fabrication for landscape architecture by focusing on the robotic applications and tools currently used in architecture. To do so, we conducted an extensive systematic review of the existing research and projects of the most renowned institutions in the field of robotic fabrication and computational design that have established digital construction laboratories for extensive research and experimentation. Namely, ICD/ITKE (URL-1), Gramazio Kohler Research group (URL-2), Kokkugia (URL-3), Neri Oxman's Mediated Matter (URL-4), DFAB (URL-5), and ZHA Code (URL-6). First, we excluded the irrelevant projects with no relation to robotic machines and restricted the projects to the recent 15 years, extending from 2008 to 2022. However, as we observed that the sampled research before 2012 stood as outliers, the time frame was limited further, and a total number of 65 research projects were identified from 2012 to 2022. They were transmitted into an Excel database. We classified all the data based on their main aspects and analyzed them under the themes of use of material, the implemented task, the final product, and the project's goal, which were subcategorized into the four main themes of productivity and efficiency, sustainability, safety, and new possibilities. First, we sorted all category data chronologically to find the most and minor focus within years. Afterward, we also matched the final products with their goal and material in a separate excel sheet to detect the existing gap in robotic projects more in detail. Figure 1 shows the research workflow, and Table 1 demonstrates the list of reviewed cases.

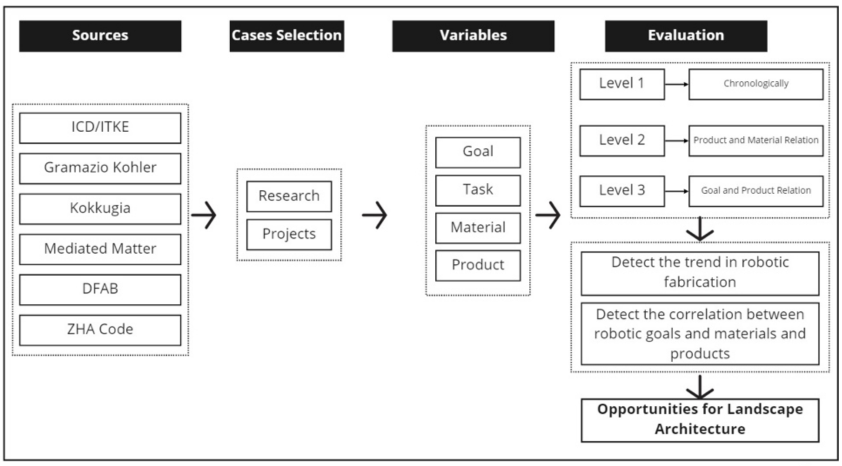

Figure 1- Workflow of the research

Table 1. The List of Reviewed Cases (URL 1,2,3,4,5,6)

Source	Project titles and years
DFAB	Mesh Mould and In situ Fabricator (2017), Lightweight Flexible Formwork (2018), Large-Span Self-Supporting Assemblies (2019), Spatial Timber Assemblies (2020), Performance-Integrated 3D Printing (2021), Moldless Shaping of Concrete Elements (2022)
Gramazio Kohler	Flight Assembled Architecture (2012), Echord (2012), BrickDesign (2012), TailorCrete (2013),Acoustic Bricks (2014), Mesh Mold (2014), Topology Optimization of Spatial Timber Structure (2015), Smart Dynamic Casting (2015), Aerial Construction (2015), YOUR Robot Programming (2015), Mobile Robotic Tiling (2016), Robotic Integral Attachment (2016), Spatial Wire Cutting (2016), Robotic Cosmogony (2017), Sisyphus (2017), Spatial Timber Assemblies (2018), Prefabrication with Smart Dynamic Casting (2018), Mesh Mold Metal (2018), DFAB House (2019), Digital Ceramics (2019), RobotSculptor (2020), Jammed Architectural Structures (2020), Robotic Fabrication Simulation for Spatial Structures(2020), Deep Timber (2020), Adaptive Detailing (2020), FrameForm (2020), The Folded Concrete Structures (2020),Data Science Enabled Acoustic Design (2021), RIBB3D (2022), (Heap)Autonomous Dry Stone(2022), Eggshell (2022), Timber Assembly with Distributed Architectural Robotics (2022), Robotic Plaster Spraying (2022), Human-Machine Collaboration (2022)
ICD/ITKE	Landesgartenschau Exhibition Hall (2014), Hive: A Human and Robot Collaborative Building Process (2015), Elytra Filament Pavilion (2016), ICD Sewn Timber Shell (2017), Cyber Physical Macro Material (2017), MoRFES_01: Mobile Robotic Fabrication Eco-System (2017), ICD Aggregate Pavilion (2018), BUGA Wood Pavilion (2019), ITECH Research Demonstrator (2019), BUGA Fiber Pavilion (2019), Fiber Façade (2020), Maison Fiber (2021), livMatS Pavilion (2021), Bio-composite Façade Panel (2022)
Kokkugia	Extruded Inlay (2012), Fibrous Concrete (2013), AADRL Arial Robot Thread Construction (2015), AADRL Swarm Printing (2015)
Mediated Matter	Spider bot(2014), Digital Construction platform (2017), Fiberbot (2019), Aguahoja III (2022)
ZHA Code	Thallus Installation (2017), Striatus 3D Printed Concrete Bridge (2021)

4 Results

4.1 Goals

Extracted from the literature, architectural robotic fabrication goals were classified and analyzed into four main themes: productivity and efficiency, sustainability, safety, and new possibilities to construct things we were unable to previously. As demonstrated in Figure 2, the proportion of studies with efficiency goals surpasses the others. Additionally, new possibilities and then. sustainability covers a large area in robotic applications. However, safety has been the mainly ignored goal.

As shown in the chart, productivity and efficiency had a slightly fluctuating trend which experienced a sharp fall in 2021, followed by another fall in 2022. As the second most popular goal among research projects, the number of new possibilities has gradually declined after 2016. Whereas it bucked the trend in 2022 and started growing again. Furthermore, although low initially, sustainability goals have increased enormously after 2017. Safety, the most ignored goal, has recently received little attention.

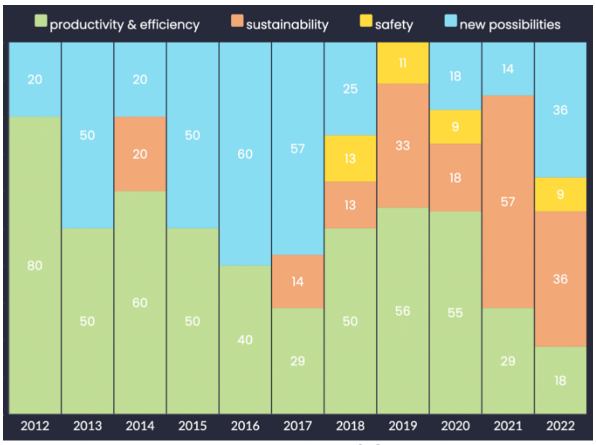

Figure 2- Distribution of Goals

4.2 Implemented Tasks

As a result of the analysis, the authors have identified numerous tasks implemented in architectural robotics research and projects. These tasks include assembly, 3Dprinting, moldless fabrication, sculpting, formwork development, casting, structure reinforcement, slip forming, in-site fabrication, hot-wire cutting, bricklaying, welding, simulation, milling, spraying, winding, jamming, tool or process development, sand suction, and creating suspension spaces. As shown in Figure 3, the most popular robotic task among architects is assembly. Considering that robotic assembly is a critical phase in the workflow from design to construction and the ultimate expression of a robotic fabrication system is in the assembly of the structure, the obtained outcome is not a surprise. 3Dprinting and in-site fabrication are also among the most utilized tasks. A detailed look at the chart also discloses the chronological trends of these tasks. Though the fluctuations in the number of assembly projects, the trend rose in 2019 and remained almost constant after a slight decrease in 2020.

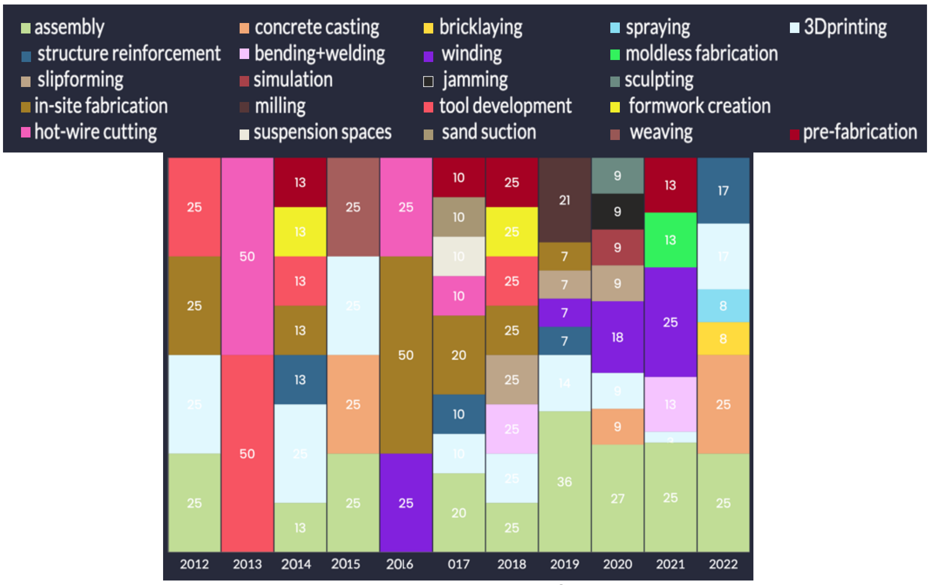

Figure 3- Distribution of Tasks

4.3 Utilized Materials

The analyzed projects have shown great diversity in terms of utilized materials. These materials contain concrete, timber, brick, metal, fiber composite, and plastic as the most popular ones. However, stone, plaster, sand, ceramic, clay, bio-materials, and much more are among the materials used in these projects. Though covering a considerable proportion of materials in robotic applications, the timber had been mostly ignored until 2014, when it experienced a significant shift. Followed by an increasing oscillation and reaching the peak in 2019, a gradual decrease was observed afterward. Despite this reduction, timber remains the most in-demand material in recent years (Figure 4). Likewise, concrete has been highlighted after 2013. It was on the rise with slightly varying patterns. Notwithstanding the concrete and timber, brick has received the proper attention from the beginning of the period. However, it has lost its initial popularity in recent years.

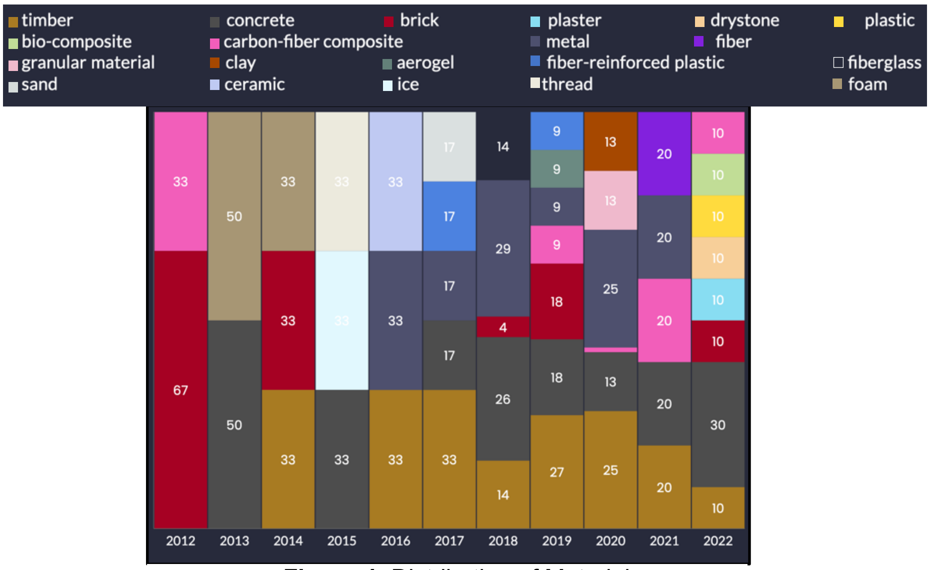

Figure 4- Distribution of Materials

4.4 Final Products

The review of the implemented projects provides various products in structures, pavilions, façades, mesh mold, construction objects, floating objects, sculptures, robots, and tools and frameworks. To clarify, structures include footbridges, slabs, frames, and walls. At the same time, tools and frameworks cover novel fabrication processes, construction platforms, and design software. Since 2013, many products have been devoted to structures. On the other hand, pavilions and tools are the second most popular robotic products, covering almost one-third of all. While tool/framework quantity maintained an almost constant pattern, the number of pavilions disregarded the trend with its highest rate in 2019.

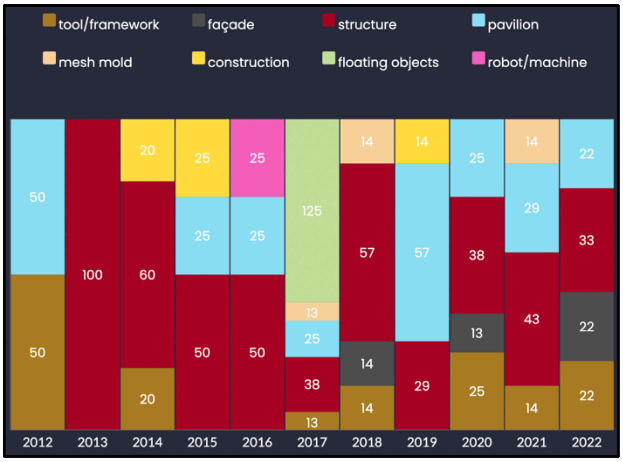

Figure 5- Distribution of Products

4.5 Correlation between Goals, Products, and Materials

As an additional step, a separate Excel sheet was created to match the most popular products with their extensively used materials and goals. The popular products were extracted in the previous step as structures and pavilions. Tools and frameworks were excluded from the product category because they mostly do not contain any materials. As illustrated in Figure 6, structures mainly utilized concrete and timber for productivity, efficiency, and safety purposes. Moreover, pavilions involved a wider variety of objectives: sustainability, new possibilities, and safety. Fiber-reinforced composites are the most significant materials used in pavilions.

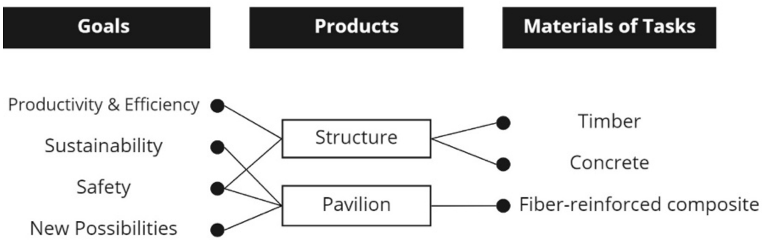

Figure 6- Correlation between the Most Popular Products, Goals, and Materials

5 Gaps and Opportunities

Finally, we summarized all the variables based on their most frequent attributes from 2012 to 2022 (Table 2). Gathering all the data together would help us better detect bottlenecks or potentials. The first potential in applying robotic fabrication in landscape architecture is related to the goals of reviewed projects (Figure 2). Sustainability, as an essential element in landscape architecture, played a significant role in some of the recent projects. The ever-rising focus on sustainability, especially after 2017, shows the attempt to prioritize this goal. Considering architectural robotics' most prevalent materials, sustainable and unsustainable resources were discerned. Even the allocation amount of sustainable materials varies. While more conventional types of sustainable materials like timber have been widely used, materials like fiber composites and bio-composites are less employed.

On the other hand, the most common tasks in architectural robotic fabrication include assembly, 3Dprinting, and in-site fabrication. While assembly and 3D printing maintain an increasing use, in-site fabrication tasks have seen a dramatic fall in 2020 (Figure 3). This gap highlights the previously mentioned intrinsic complexity of the reality of on-site robotic fabrication in landscape architecture. That is why the on-site robotic fabrication of landscape architecture cannot go beyond the automation of the existing techniques.

Additionally, 3Dprinting, as an essential task in architectural robotics, faces boundaries in the realm of landscape architecture. Often used for large-scale areas, landscape architecture planning and design combine natural elements like vegetation. Due to financial and physical limitations, current 3D printing technology cannot support such situations. According to the literature review, one of 3D printing's constraints is speed, which makes it challenging to use the technology in most sectors because it takes a long time to produce a large-scale model (Easley et al., 2017).

Table 2. Most Popular Variables based on Years

	Goal	Task	Material	Product
2012	Efficiency	3Dprinting	brick	pavilion+tool
2013	Efficiency+ New possibilities	tool development+hot-wire cutting	concrete	structure
2014	Efficiency	3Dprinting	timber + brick	structure
2015	Efficiency+ New possibilities	3Dprinting	concrete	structure
2016	New possibilities	in-site fabrication	timber+metal	structure
2017	New possibilities	assembly+in-site fabrication	timber	structure
2018	Efficiency	3D printing	concrete+metal	structure
2019	Efficiency	assembly	timber	pavilion
2020	Efficiency	assembly	timber+metal	structure
2021	Sustainability	assembly+winding	concrete+timber+metal	structure
2022	Sustainability+New possibilities	assembly+concrete casting	concrete	structure

6 Conclusion & Future Work

This paper addressed the robotic applications in the field of architecture to examine the possibilities it can offer to landscape architecture. For that purpose, existing research projects of the most renowned architectural research labs were overviewed in four main categories: goals, materials, tasks, and products. Figure 7 shows some of the reviewed projects. As a result of this research, we spotted both the gradual and sharp chronological changes in each theme. Additionally, we were able to discover the correlation between the subjects. This approach helped us to highlight the gaps and opportunities in the realm of robotic landscapes. We believe this research will be essential in bridging the gap between landscape architecture and robotic fabrication and provide a roadmap for landscape architects.
However, the scope of the research is constrained in terms of the comprehensiveness of the research labs. As a future step, we plan to collect more projects from different research groups and increase our dataset.

Figure 7- Heap (URL-7), Thallus Installation (URL-8), DFAB House (URL-9), Maison Fiber (URL-10), BUGA Fiber Pavilion (URL-11), Jammed Architectural Structure (URL-12), livMatS Pavilion (URL-13), Fiberbots (URL-14)

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