Changing Paradigm: a Pedagogical Method of Robotic Tectonics into Architectural Curriculum

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Abstract –

With the rapid spreading of digital technology and automated construction applications in architecture, engineering and construction (AEC) society, the current trend is becoming clearer, that automation will change the way we design and build. Robotic Tectonics, as a part of automatic construction methods aiming to achieve the integration workflow from architectural design to finial construction products, emerged from architectural profession for a decade. Avant-garde architects explored the possibility of this new design paradigm through creating the integration of digital design software within the simulation and controlling of robotic construction, and only recently, this completed digital workflow pushes architectural design to re-control the process from initial design conception to finial physical construction, guiding the AEC industry towards a precise, efficient, thus more sustainable development.

However, a success technology innovation is based on the widespread acceptance, where education plays an important role, but in the current architectural education, there is barely no professional courses focused on this. The need to find a framework to integrate the robotic tectonics workflow with architectural curriculum is increasing. Therefore, it became mandatory to integrating and testing of the complete robotic tectonics workflow into architectural curriculum.

In this paper, a pedagogical method of robotic tectonics is defined through a linear scenarios of four stages, based on experiences gleaned from 'Robotic Tectonics' workshops and various other teaching practices. Then this pedagogical method is tested into an architectural curriculum with 135 undergraduate students, for each student, the complete participation of the overall process and questionnaires is required. Results shows this pedagogical method introduces multi-layered interdisciplinary knowledge to architecture students and enables them to using related technologies of robotic arms for automated construction practices, changing the paradigm of architectural curriculum for new design and build processes that will redefine architecture in the near future.

Keywords –

Robotic Tectonics; Architectural Education; Pedagogical Method; Digital Workflow; Architectural Curriculum

1 Introduction

As the industrial revolution replaces manpower with machines to produce large-scale production, it will gradually change our production and lifestyle. Automation technology becomes the key to accelerate transitions of the manufacturing industry from traditional inefficient and labor-intensive mode to present an opportunity to do things more efficiently, accurately, and creatively. As the most representative tool to promote the wave of automation technology, robots have been widely used, especially in the automotive industry. However, like every technological upgrade process, the field of architecture, engineering, and construction (AEC) industry is still in an exploring period of shifting the conventional technology to the advanced technology.

Nevertheless, a bunch of advanced technology applied into AEC industry has enlightened a digital future for the architectural design field, the combination of parametric design tools, design and multi-data simulation, automated construction and robotics. The most advanced technologies start shifting the conventional design methods to the next efficient design workflows. This brings the opportunity to fully realize MacLeamy's curve which advocates shifting design effort forward in the project, frontloading it, in order to archive high-efficiency design process and high-performance architecture eventually (Figure 1). Following the pavement contributed from the avant-garde architects, like Fabio Gramazio and Matthias Kohler in Zurich, and the demonstration of developing a workflow that challenged the current limitations of computational digital fabrication in design and construction, we believe the relevance of Advanced Architectural Design method with Robotic Tectonics is growing, and it may have the potential to serve as the catalyst for the automation of construction across the diverse architectural field [1,2].

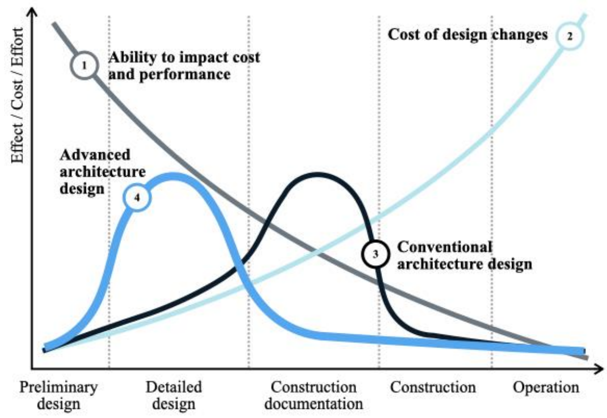


Figure 1. MacLeamy's curve which advocate shifting design effort forward in the project, frontloading it, in order to archive high efficiency design [3].

Therefore, it is necessary to provide future architects in advance with training in new technical techniques and methods suitable for the development of the industry at the educational stage. We believe that successful technology innovation is based on widespread acceptance, where education plays an important role. In recent years, a few of the world's top universities have begun to combine robot manufacturing technology with curriculum design in various forms, such as the representative Harvard University, Carnegie Mellon University, University of Michigan and Princeton University in the United States, University of Stuttgart, ETH Zurich and Delft University in Europe, and Tsinghua University and Tongji University in China, etc. Those are successfully revealed the potential of combining the most frontier advanced robotic technology with the pursuit of humanities and art into the architectural design method under the core concept of architectural tectonics though still at the practice stage. Moreover, we could witness that the ability of robotic tectonics is growing, are advancing in such an efficient and incomparably unstructured environments, as well as has the potential to serve as the necessitated trigger for construction automation in a numerous and diverse field in the future.

From 2015 to the present, we have been eagerly making efforts to find a framework to integrate the robotic tectonics workflow with the architectural curriculum and make it became mandatory to integrating and testing of the complete robotic tectonics' workflow into the architectural curriculum. Thankfully, the feedbacks and opinions collected from students proved that our teaching practice is effective and worthwhile.

2 Pedagogical approach of Robotic Tectonics workflow

with the interdisciplinary requirements and technical difficulty of robotic tectonics, how can we integrate it into architectural education in a simple and understandable way that could allow students to master the necessary skillset while addressing the critical challenge of sustainable development in architecture? As a response to this challenge, we are pushing to establish a novel workflow that can act as a model for a digitally-focused pedagogy and define it within a sustainable framework that combines advanced robotic technology and architectural tectonics. We intend to focus on construction techniques driven by robotics in order to significantly improve material, structural, energetic, and procedural efficiency, all while promoting the aesthetic innovation emblematic of an architectural education. In this linear model, we aim to test the integration of a variety of interdisciplinary techniques in the early design stages, which we believe will aid in the advancement of sustainable development, that changing the paradigm of architectural education. [4-7].

Since its induction in 2016, DAMlab (digital architecture & manufacturing laboratory) has established an experimental teaching platform exploring a myriad of digital tools including 3 KUKA robots (KR120R2700, KR60R2100, KR9R1100) and various CNC machines. Since then, we have hosted several workshops focused on the topic of robotic tectonics. From these last three years of teaching practices, a prominent didactic pedagogical approach has emerged. This new pedagogy is a fully comprehensive robotic tectonic workflow, but it is more easily understood through its four stages – **Parametric Design**: A parametric model-based design conception, **Multi-data Simulation:** robot-oriented multi integral data virtual simulation, **Robotics Application:** Construction-aimed robot end effector development, and **Robotic Construction:** Robotic tectonics represented through automated construction. Within the confines of these individual stages, students can easily break down this overly complex and technically difficult workflow into successive phased steps which each contribute to the learning objectives of this new pedagogy, while simultaneously experience the integrated design to construction workflow which attempting to realize the frontloading concept of

MacLeamy's curve for high efficiency design. (Figure. 2)

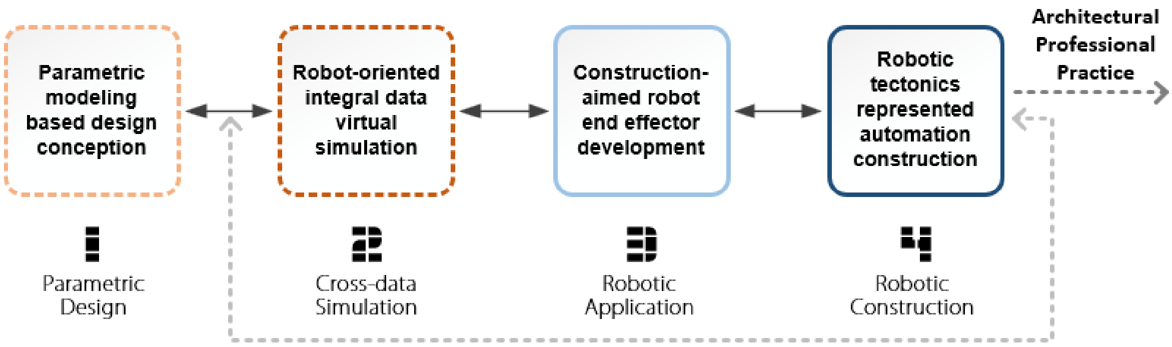


Figure 2. Workflow of the Robotic Tectonics [8]

This pedagogical approach explores the entirety of the typical design and construction cycle, providing the necessary technical skills required to make automated construction into a reality. It expresses a global initiative for students to understand and apply contemporary technology to critical thinking in order to pursue design innovations towards a more sustainable future. Leaders in automated construction practices must be proficient not only in traditional computational and technical skills, but also in a new form of digital materialization which includes a critical understanding of constantly changing manufacturing processes [8].

3 Bricklaying experiment for Robotic Tectonic curriculum courses

The pedagogical method is tested into an architectural curriculum with 135 undergraduate students, for each student, the complete participation of the overall process and questionnaires is required. Our experimental course is conducted in groups. The task of course is to build a columnar brick structure within the range of 0.9m*0.9m*2m, using the standard bricks (200mm*100mm*50mm). The 6-axis KUKA KR30HA robot is applied in this experiment. The robotic arm vertical range of activity is from +35° to -135° with a large turning range of 185° in both directions.

3.1 Pedagogical purpose for bricklaying experiment

The purpose of this course setting is to let students to fully experience the entire robotic tectonic process to systematic understand:

- The theoretical concepts and workflows of "Robotic Tectonic" from design to construction.
- The "Robotic Tectonic" is a combination of Interaction between material and construction, clear and logic structure, and performative architecture.
- The current trends in architectural design and construction technology.
- The modeling and programing techniques, as well as the basic robot working logic and operation skills.

3.2 Experimental content

The four stages of the workflow contents virous works of different levels of interaction, such as information interaction between parametric design and virtual simulation, the parametric design provide geometry generation, program definition, etc. to the virtual simulation process, and get feedbacks as multi-data information, visual configuration, etc. to change design decisions. All these contents are opened reachable for students to experiment with, the whole workflow of experiment contents is illustrated on figure 3.

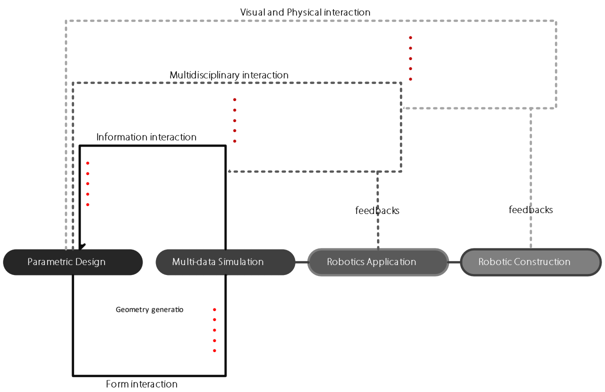


Figure 3. experiment content of Robotic Tectonics workflow

3.3 Bricklaying experiment

3.3.1 Concept and overlapping logic

The priority of a brick structure is to design the overlapping bricks pattern. By deconstructing conventional brick masonry structures, students can learn the brick overlap logic and its mechanical behaviour, then try to break through the inherent impression of the physical properties of the material itself and further expand the possibilities of the material in design. With the help of digital modelling technology, datum points of curved shapes are generated in Rhino software. After that, a reasonable curve shape is obtained through the algorithm and a curved surface is generated to obtain a basic shape. Then import this basic surface into the parameterized software grasshopper to analyse and arrange the bricks, further optimize the interaction between bricks and bricks by adding functional mapping, object interference and other methods to generate new overlapping logic of the brick structure.

3.3.2 Parametric design for brick structure

The priority of a brick structure design is the overlapping form between bricks. By extracting the logic of brick overlap from the traditional brick structure masonry form, and then by adding function mapping, object interference and other methods to change the interactive relationship between bricks to explore a new spatial logic for the parametric design of brick structure.

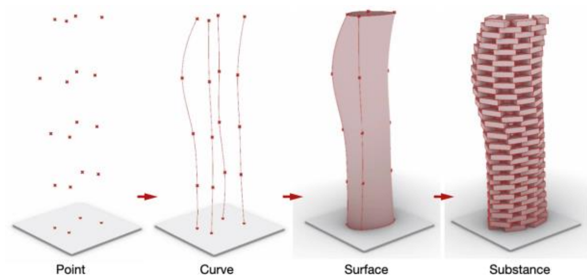
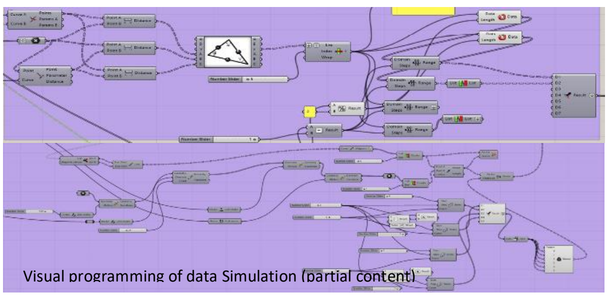


Figure 4. Parametric Design process

3.3.3 Multi-data simulation for brick assembly

The sequences of picking up each brick, reposition it, gluing at certain area on it, locate into a precise spot, and configure the overall processes for the whole structure's building sequence, are fully considered in this stage. (figure 5) Therefore, not only design factors, but also procedure factor, material information, robot operation data, signals, etc. are all integrated and simulated here.



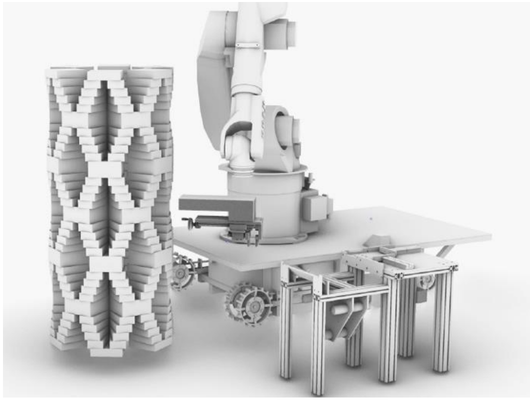


Figure 5. Process of multi-data virtual simulation

3.3.4 Robotics application for bricklaying

Robotics technology of gripper tools, sensing devices, plc components are applied to form a complete end-effector and building environment for the bricklaying.

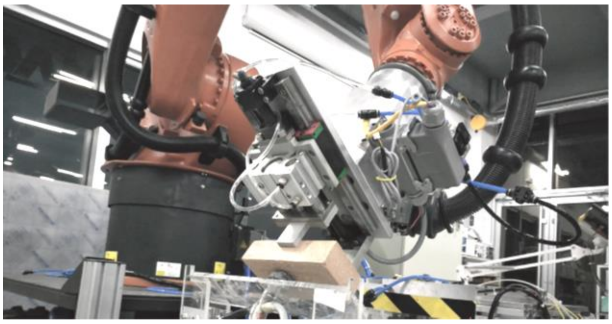


Figure 6. End-effector of robotics application for bricklaying experiment

3.3.5 Robotic bricklaying practice

After setting up the parametric design, multi-data simulation, and robotics application procedures, the final building experiment could be operated (figure 7). During this physical building process, feedbacks could also directly deliver to the previous stages, and manipulate accordingly to the current building situation.

Figure 7. Physical building process

3.4 Experiments results

During the courses, 8 groups of bricklaying experiments are completed, students participate all processes from parametric design to robotic construction. For each stage of the Robotic Tectonics workflow, students have fully experienced through building experiments. Each group of bricklaying project explored virous configurations of robotic bricklaying tectonic, the experiments achievements are fruitful. (figure 8)

Figure 8. Experiments achievements for courses

4 Teaching questionnaire survey and analysis

To explore the students' perceptions of the proposed pedagogical approach of robotic tectonics and obtain their feedback on teaching effectiveness, we conducted a questionnaire survey of 135 students in the third grade of architecture major who participated in our course. According to the survey, all students' existing relevant knowledge and skill experience of "Robotic Tectonics" has little difference before attending the course. That indicates the feedback information of the questionnaire, which could not be affected by the factor of personal experience, is valid and reliable.

4.1 Comparative analysis between before and after attending the course

The comparative analysis of the results of the questionnaire before and after the course shows in Table 1 that the students have obvious views on the impact of the "Robotic Tectonics" in the AEC industry, the position in the future architectural design and the necessity as the content of the architectural design course. Among them, the proportion of students who believe that "Robotic Tectonics has a great positive influence or plays a dominant approach" has increased from 24.44%, 45.19% (before attending the course) and 42.22% to 68.89%, 75.56% and 54.81% (after attending the course). Similarly, the proportion of students who believe that "Robotic Tectonics has a revolutionary influence or plays an essential decisive approach" has increased from 2.22%, 3.70% and 8.89% to 17.78%, 20.74% and 42.23%, respectively. Then, from the results of internal consistency analysis, the grand mean values of the above set of questions changed a lot from 2.44 to 3.20 and the values Cronbach's alpha increased from 0.442 to 0.791. It means that after experiencing the course learning, the students recognized with more uniform consistency. Most students' opinions have changed from "Robotic Tectonics has a small influence or plays an auxiliary approach" to "that has a great positive influence or plays a dominant approach" on the relevant dimensions of industry, architectural design or professional curriculum.

Table 1. Comparative analysis between before and after attending the course

	Before attending the course		
Questions / Options	Impact on future AEC industry	Role in future architectural design	Role in future architectural design courses
1: No influence / An optional approach	7 (5.19%)	3 (2.22%)	2 (1.48%)
2: Small influence / An auxiliary approach	92 (68.15%)	66 (48.89%)	64 (47.41%)
3: Great positive influence / A dominant approach	33 (24.44%)	61 (45.19%)	57 (42.22%)
4: Revolutionary influence / A necessary approach	3 (2.22%)	5 (3.70%)	12 (8.89%)
Summary of internal consistency	Grand mean	Cronbach's alpha	Sig.
	2.44	0.442	0.000

	After attending the course		
Questions / Options	Impact on future AEC industry	Role in future architectural design	Role in future architectural design courses
1: No influence / An optional approach	1 (0.74%)	1 (0.74%)	0 (0.00%)
2: Small influence / An auxiliary approach	17 (12.59%)	4 (2.96%)	4 (2.96%)

3: Great positive influence / A dominant approach	93 (68.89%)	102 (75.56%)	74 (54.81%)
4: Revolutionary influence / A necessary approach	24 (17.78%)	28 (20.74%)	57 (42.23%)
Summary of internal consistency	Grand mean	Cronbach's alpha	Sig.
	3.198	0.791	0.000

4.2 Improvement of students' design capacity

The analysis of multiple-choice question (Figure 9) finds that the majority of students of (132 people) indicated that the concept of robotic tectonics will continue affecting the architectural design. There are 90 students who reported that their logical thinking improved through the simulation process. There are 86 students considered "human-machine collaboration improves our efficiency". 79 students thought that "robotic tectonics improve the quality of our construction work". 65 students think that their innovative ability improved by using the parametric design method. Few students (29 people) have the view of "It has a positive impact in other areas that are not clear", while only one student thought "it has no help."

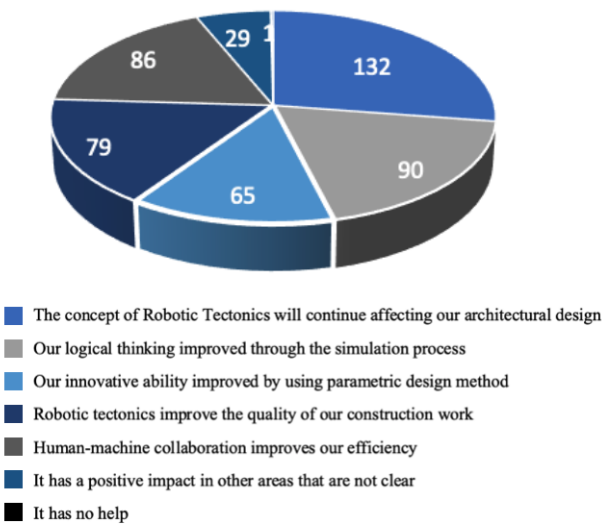


Figure 9. The questionnaire analysis of the improvement of students' design capacity

4.3 Open-ended responses

The students' open-ended responses to the survey questions overwhelmingly provided meaningful improved suggestions and personal reflections about the proposed course. Some specific comments include:

"This is the first time I have manipulated a robot. It is highly professional and requires more systematic learning. I suggest adding related auxiliary courses."

"Compared with the previous manual construction model, the accuracy of the robot construction is particularly high, and it can save labor time."

"For me, it is a magical and surprising experience to compile the design into the program and then let the robot build it into the real thing. I hope to have more opportunities in the future."

"We young people in the contemporary age should actively learn and master this new knowledge and new technology and prepare for the future in advance."

5 Conclusion

Applying the pedagogical method of robotic tectonics into architectural curriculum has significant efforts for the future participants in the AEC industry. It can be considered that the conventional architectural design concept is necessary, but it will allow students to form an inherent thinking, which has a negative effect on the acceptance of new technologies and concepts. Curriculum theory and practical education through reasonable process arrangements are effective for developing students' thinking and perceiving to adapt to the advanced architectural design concepts of the future era. The proposed pedagogical approach and its workflows are reasonable, which can make students fully understand the whole process from architectural design to construction through step-by-step teaching practices and effectively imparted advanced architectural design concepts. All analysis of the questionnaire results quantifies the beneficial effects of this course even are highly recognized and supported by students. The paradigm of architectural education is changing with the integration of emerging robotics technology.

This study reveals a pedagogical approach for future architectural education towards interdisciplinary vision of future sustainable automated construction. All new technologies need widespread for fully acceptance and manipulation, where education always plays an important way. With the digitalization transforming of every field of our lives and societies, students as the future professional participates have somehow generated consciousness for creating brand new ideas of architectural design and construction methods, which could be read through the positive attitude towards future challenges, therefore, adapting to the trends of digitalization and interdisciplinary developing for architecture, engineering and construction industry is crucial. Searching for the proper pedagogical methods for this changing paradigm are necessary, also, creative and attractive approaches for both students and other participates are indispensable, which always be the future works for our further research.

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