World Transactions on Engineering and Technology Education
Vol.17, No.4, 2019
© 2019 WIETE

Robotics in architectural education

Kacper Radziszewski & Jan Cudzik

Gdańsk University of Technology
Gdańsk, Poland

ABSTRACT: Robotics rapidly is becoming an important part of architectural design at all stages, from early conceptual work to construction. In this article is presented the present state of the art in the field related to architectural education, from computer numerical control (CNC) milling tools, through drones to multi-axis robotic arms. Professionals involved in modern design techniques often use them to create precise, complex forms that previously were not possible. This raises the question of whether and how architecture schools can provide adequate knowledge and basic skills. In this article, the authors discuss, through the example of a design course at Gdańsk University of Technology, Gdańsk, Poland, the introduction of robotics to Master's students at the Faculty of Architecture. It gives an overview of exercises, requirements, results and evaluation.

INTRODUCTION

New technologies rapidly are becoming an important element of architectural design. Nowadays, architects not only use software as design tools, but also apply other design methods such as digital fabrication. The application of digital tools is apparent in many contemporary designs. Industrial robots can be described as an extension of hand tools controlled with a computer, as Koren wrote:

> *Industrial robots are actually mechanical handling devices that can be manipulated under computer control. [...] The mechanical handling device, or the manipulator, emulates one arm of a human being and similarly has joints, denoted sometimes as shoulder, elbow, and wrist. The wrist contains pitch, yaw, and roll orientations. The joints are driven by electric, pneumatic, or hydraulic actuators, which give robots more potential power than humans* [1].

The main digital fabrication technique is applied through a computer numerical control (CNC) milling machine. It is relatively cheap and easy to control and produces predictable results. Modern CNC milling machines allow extremely precise and repetitive processing of a wide range of materials applied in the building industry. However, contemporary architectural design education is based on research methods, which lead to more universal production methods of fabrication. This creates a challenge as to whether and how architecture schools could provide adequate knowledge and basic skills for programming digital tools, as Pęczek and Cudzik opined:

> *In practice, it means that students are encouraged to communicate with a digital machine beyond the haptic interface offered by the system manufacturer. It involves learning some basic and advanced computer programming language skills* [2].

ROBOTICS IN ARCHITECTURE

To expand the skill set of students it is important to apply a variety of problem-solving tools, one of which is robotics. Robotics is no longer a future solution and is significant for architecture. Introducing robotics to architecture started with small-scale experiments.

One of the first experiments was conducted by the Swiss Federal Institute of Technology in Zurich, at a studio led by Gramazio and Kohler, where a new technique for creating brick patterns was developed. Designers employing a robotic arm created a prototype for the façade of the Gantenbein Vineyard. The façade was manufactured entirely by a robotic arm on a digitally controlled platform. This allowed a designer to create a unique, complex and precise brick pattern that was applied to the Vineyard façade in 2006. The robot was responsible for the placement, rotation and handling of bricks:

The robot accurately placed the material based on digital data that describes the desired horizontal and vertical placement and orientation [3].

A system similar to a 3D printer, but without the scale and spatial limitations, was developed for the wave Pavilion created by Supermanoeuvre and Matter Design in 2010. This provides for a wide scope of applications for new fabrication solutions:

Using a multi-axis robot refines the process of sequential layering by allowing the addition of foam from any angle. This lends more flexibility to the staging of additions ... because the foam is more capable of withstanding bending and tension [4].

Another example of robotic application in the architectural design is the manufacturing process designed by Coop Himmelb(l)au for Shenzhen Museum. Architects created a method allowing a seamless form of large-scale sculpture made of polished stainless steel to become the main element of the museum interior. To use long range digital fabrication, architects employed a production method based on a mobile railway track and two 6-axis robotic arms. With different tools, the whole design was accomplished entirely by applying digitally controlled tools. The created form as a main element of the building was described by Prix as:

A silvery, shining and softly-deformed Cloud *serves as a central orientation and access element on the Plaza. On several floors, the Cloud hosts a number of public functions such as a cafe, a bookstore, and a museum store and it joins the exhibitions with bridges and ramps. With its curved surface, the Cloud opens into the space reflecting the idea of two museums under one roof* [5].

Robotics opened up architecture towards complex and extremely precise geometries. A good example of such a design is the ICD/ITKE Research Pavilion created by Achim Menges and his team from Stuttgart University of Technology. The most challenging part of the digital fabrication was the creation of a double-curved module fabrication system that used two 6-axis Kuka robots:

[A] robotic coreless winding method was developed, which uses two collaborating 6-axis industrial robots to wind fibers between two custom-made steel frame effectors held by the robots. While the effectors define the edges of each component, the final geometry is emerging through the interaction of the subsequently laid fibers. The fibers are at first linearly tensioned between the two effector frames. The subsequently wound fibers lie on and tension each other which results in a reciprocal deformation. This fiber-fiber interaction generates double curved surfaces from initially straight deposited fiber connections [6].

The form created by Menges and his team is an example of how robotics can change contemporary architecture aesthetics and form-finding processes. Therefore, it is highly relevant to create appropriate teaching methods and adjust the teaching programmes at faculties of architecture.

TEACHING METHOD

Architectural research continues in education, and in the Faculty of Architecture at Gdańsk University of Technology robotics was introduced in 2017. The first class took place in spring of 2018. Before taking the elective seminars, students completed a series of classes from descriptive geometry and mathematics, through arts and sculpture to 3D modelling (see Figure 1). Mandatory classes before taking Robotics in Architecture were digital fabrication or programming aided 3D modelling. These classes introduced new design techniques and gave the opportunity to practise skills necessary for learning how to control a robotic arm and to use it for design.

Field	Subject						
Arts	Art Workshop I	Art Workshop II	Art Workshop III	Art Workshop IV	Sculpture	Composition	
Descriptive geometry	Descriptive Geometry I	Descriptive Geometry II					
Mathematics	Mathematics I	Mathematics II					
3D modelling	CAD I	CAD II				Advanced CAD	Robotics in Architecture
Digital fabrication						Elective Seminars	Elective Seminars

Figure 1: The teaching pattern at Gdańsk University of Technology.

During the class, 30 students, divided into six groups of five, had an opportunity to experiment with robotics in architecture. Dividing students into teams improves students' performance by introducing competition between groups [7]. Students were tutored by two lecturers: Kacper Radziszewski and Jan Cudzik. During class, students worked primarily with McNeel Rhinoceros 3D CAD modelling software, Grasshopper software development systems and with additional plugins, including Kuka|prc (Keller und Knappich Augsburg) that enable simulations and robotic arm control. Students had the opportunity to work with a medium payload 6-axis robot, Kuka KR60HA equipped with custom design holders for selected tools: flashlight, permanent marker and hot-wire (see Figure 2).

The students who studied the course previously had taken elective seminars that covered the issues of basic parametric design with Rhinoceros and Grasshopper. This gave a strong background for new and challenging experiments. An important aspect was the workspace elements that were fabricated before classes. Each of three design tasks required a new setup, tool and robotic arm configuration. Therefore, they need to be well organised and students must prepare designs on time. To introduce students to advanced robotics fabrication, there were three main exercises and the introduction, with more complex aspects gradually introduced. The introduction covered several basics, and these were work safety, arm movement mechanics, control panel handling and manual movement.

a) b) c)

Figure 2: End-effectors: a) flashlight held in cramp; b) marker holder; and c) hot wire cutter.

EXERCISE 1: 3D LIGHT DRAWING

The first exercise introduced students to the basics of 6-axis robotic operations and programming. The task was to create a light sculpture using a robotic arm. The process employed a long-exposure camera to capture the movement of a light source to create a linear form as an aerial drawing. The initial task was limited to movement path programming, which excluded tool setup introduced in the subsequent exercises. Long-exposure movement capture was achieved through a single photo with exposure of 15 seconds. To create a clear representation of the arm movement, a strong light source was the robot end-effector. The end-effector was designed and fabricated with fused deposition modelling (FDM) technology. The tool in Figure 2a is a cramp securing the led flashlight.

Each group was instructed to create a single path, representing the three-dimensional geometry of their own choice, as shown in Figure 3. The movement was restricted to 15 seconds, to equal the exposure time of a single photo shot. The path was divided into parts with different movement speeds, which resulted in a diverse intensity of the light path. Another requirement of the programmed movement was the direction of the end-effector plane, which should target the camera lens. Programming this was most challenging because of to the various plane positions. During the exercise, students adjusted by trial and error the geometry of the path and the scale of the three-dimensional model; this required movement speed adjustments for every modification.

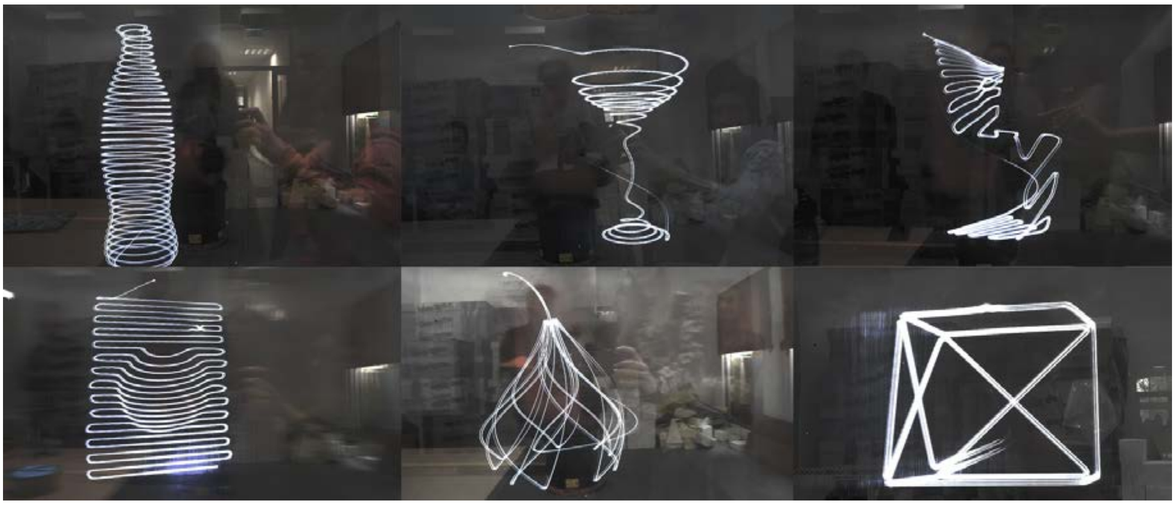

Figure 3: Examples of long-exposure 3D drawing.

Two approaches were undertaken by students: programming the movement path itself, and modelling a three-dimensional object, converting it into the series of points that generated the movement paths (see Figure 3). During the first exercise, students learned how to control the robotic arm and consider its limitations, such as range limits and axis movement speed limits. The task also involved the manual control of the robotic arm with different speed and purpose. In the first task it was also important to master the robotic arm control software. This task did not involve programming the specific tool.

EXERCISE 2: 2D DRAWING

The second task was based on a two-dimensional physical drawing introducing two essential principles of robotic fabrication: tool programming and collision. A custom robotic end-effector was designed, allowing accurate drawing. The tool was digitally fabricated with a fused deposition modelling (FDM) 3D printing process, with high density infill from polyacid plastics. The designed end-effector could hold a variety of felt tip types, up to 15 mm in diameter.

Each student group was required to program the tool on their own, by a five-point calibration process and by specifying the weight of the tool. Along with the tool, each group was required to programme a working area, by measuring and orienting the physical drawing area and reconstructing it within the digital workspace. No restrictions were given regarding the drawing design, apart from the maximum dimensions of 500 mm by 700 mm (see Figure 4).

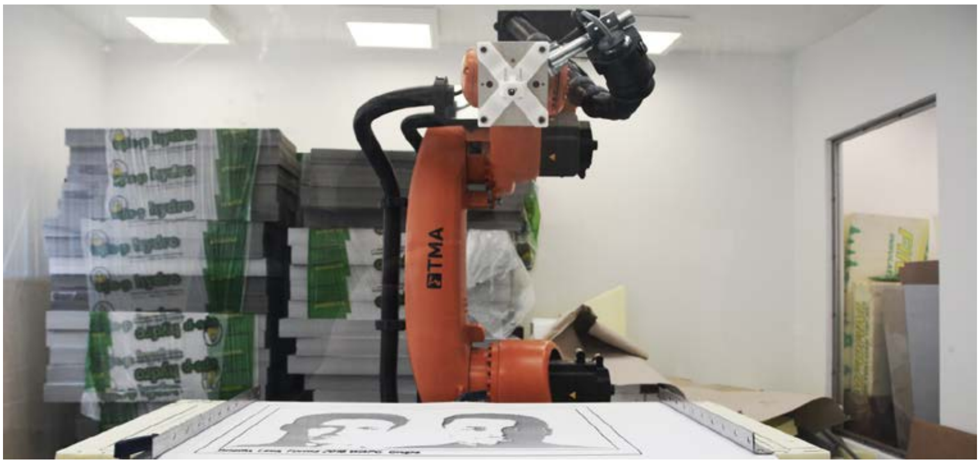

Figure 4: 2D drawing setup.

Participants employed various techniques in creating digital vector drawings, from algorithms to convert photos into linear representation, to standard CAD drawings. Several suggestions were introduced to optimise the fabrication process. The first concerned sorting the curves in a way that reduced the time spent by the robotic arm moving between drawing paths. The second suggestion was to join the drawing curves into polylines, to avoid dividing the curves into segments. Apart from the two main principles of tool programming and collision avoidance, drawing an image with separate paths required introducing retraction-withdrawal of the tool at a fixed amount above the material, to move the felt tip between successive drawing paths.

Each of the groups had to program the algorithm allowing for tool retraction, which is essential during more complex 6-axis robot fabrication processes, such as cutting and milling. Students took different approaches while designing the drawing path. Apart from computer drawing, algorithmic methods were applied: image contouring metaballs algorithm [8] and vector fields [9] (see Figure 5). Each of the fabrication processes was preceded by a simulation using Kuka|prc software, visualising possible collisions with material and the environment, and verifying the robotic arm working area. The aim of the exercise was to introduce several robotics fabrication elements: working area programming, tool fabrication methods and calibration, collision avoidance and advanced robotic arm movement path programming.

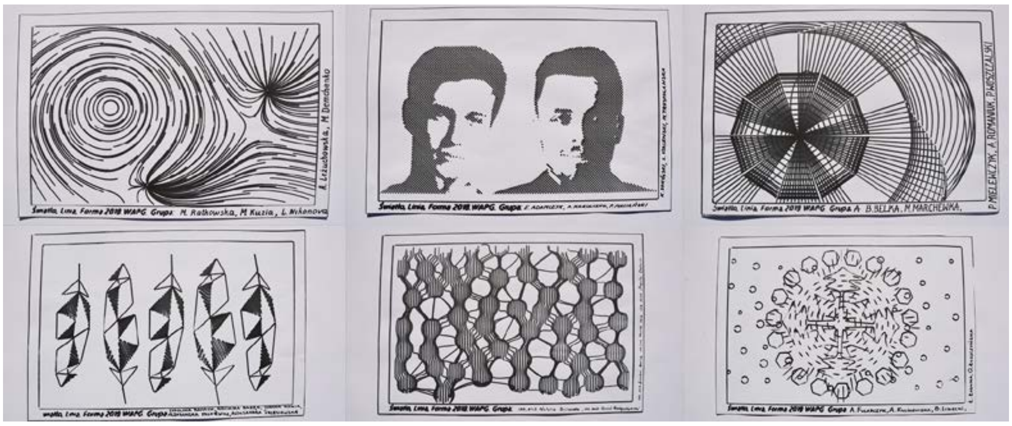

Figure 5: Robotic drawings.

EXERCISE 3: 3D WIRE CUTTING

The aim of the final exercise was to introduce students to three-dimensional digital fabrication. By combining the skills obtained during the previous tasks, which involved basics of robotics movement, programming and robotic arm limitations, participants were able to fabricate volumetric geometry. The last task was the most complex and challenging as it required the subtractive fabrication method. The exercise was based on cutting 300 mm edge styrofoam boxes with the hotwire attached to the robotic arm end effector. The tool measured 1,200 mm (wire) length with a frame depth of 300 mm. This was attached to the robot's 6th axis plate with a custom-designed 3D printed holder, allowing for a stable position of the hotwire.

As mentioned above, a custom material holder was fabricated: a platform having a flat square surface with 300 mm edge placed at the height of 800 mm reduced possible collisions during the fabrication with the long-span hotwire cutter. The process of melting the pathway of the hotwire in the styrofoam solid required adjustment of the speed. The speed affects the melting process, which can mean different outcomes, even with identical programmed movement paths. The high movement speed may not be sufficient, resulting in physical resistance of the material, which can be a cause of wire damage or material displacement.

Programming the movement at an extremely low speed of the robotic arms causes thick material layer subtraction as a result of the melt time. Adjusting the speed of the hotwire cutter should be done beforehand through trial and error. Its value is based on wire resistance and diameter, power applied, material properties and the cutting length.

Students were allowed to take different approaches towards modelling, programming and fabrication. Some objects were produced from a single piece of material, and others were assembled from fabricated elements. Additionally, two projects required rotating the cutting object, between consecutive programmed paths (see Figure 6).

Figure 6: The process of hotwire-cutting with robotic arm.

Each group was instructed to program the wire middle point as the robot's calibration point. Because of the length of the tool and possible collision with the workspace elements or the robot itself, a three-dimensional model of the tool was prepared as a digital simulation in Kuka|prc software (see Figure 7).

Figure 7: Forms achieved with wire-cutting.

COURSE EVALUATION

Students were deeply involved in the design task and considered it a path to the future. In the survey conducted after the class, students were asked to answer four questions rating the course on innovative character, skills obtained, schedule and overall rating. The range of marks was limited to between 0 and 10. The students answered the post-course survey and with 22 fully completed surveys out of a total of 30. Researchers agreed that this was a representative sample necessary to conduct the test. To obtain objective results the survey was anonymous.

Survey results are shown in Figure 8. The overall course rating was 9.59 out of 10. The innovative character of the course, which was described as a subject undertaken by students allowing in future taking part in projects in developing areas of architectural design, was rated 9.45 out of 10. The rankings are high and show directly that new digital tools are welcomed by young students and academics. Moreover, the students understood the need to learn new skills, regarding both programming and digital fabrication, which was rated 9.45 points out of 10. This shows that the need to teach new skills in the field is also high.

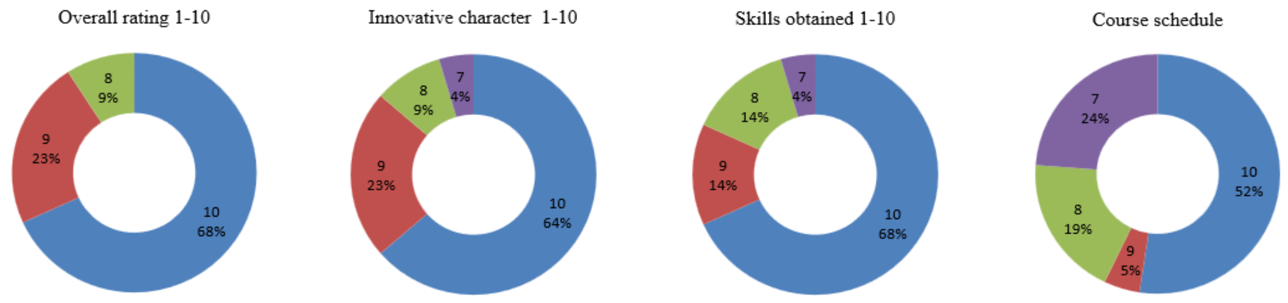

Figure 8: Summary of survey conducted after classes.

The last question was dedicated to the schedule, which assumed a full course over the period of 1 week, 8 hours each day, taking up to 40 hours in total. The students rated the course schedule 7.86 points out of 10, often pointing out that the intensive nature of the course should be taken into consideration for upcoming classes. The elective seminar was a big success. Many more students applied for the seminar, but open seats were limited. The exercise will be repeated and developed in the future.

CONCLUSIONS

Digital tools nowadays are a necessity for architects and designers. Contemporary aesthetics and functional requirements require the introduction of up-to-date technologies. Inventions drive the growth of the discipline and it is fortunate that more professionals are taking notice. The application of robotics can achieve spectacular effects, such as the ICD/ITKE Research Pavilion. The robotics and other digital fabrication tools will have a significant role to play in the future of both architectural design and education.

It is crucial to work out strategies for introducing them gradually into architecture as this gradual transition is important in education. The educational system must be prepared for change, as was previously so with the introduction of computer-aided architectural design tools and 3D modelling. The findings of this study clearly show that students are ready for the change. The introduction of various digital fabrication techniques will improve the diversity and quality of architectural design.

REFERENCES

1. Koren, Y., *Robotics of Engineers.* New York: McGraw-Hill Book Company, 1-50 (1985).
2. Pęczek, G. and Cudzik, J., Hybrid design approach in education using a progressive rule-based digital design development. Sopot College experiences. *Architecturae et Artbis*, 1 (2014).
3. Iwamoto, L., *Digital Fabrications. Architectural and Material Techniques.* New York: Princeton Architectural Press, 39-40 (2009).
4. Dunn, N., *Digital Fabrication in Architecture*. London: Lawrence King Publishing, 112-114 (2002).
5. Prix, W.D., Museum of Contemporary Art and Planning Exhibition. Shenzhen, China, *Oz*, 38, 58-62 (2016).
6. Doerstelmann, M., Knippers, J., Menges, A., Parascho, S., Prado, M. and Schwinn, T., ICD/ITKE Research Pavilion 2013-14: modular coreless filament winding based on Beetle Elytra. *Architectural Design*, 85, 6 (2015).
7. Calnon, M., Gifford, C.M. and Agah, A., Robotics competitions in the classroom: enriching graduate-level education in computer science and engineering. *Global J. of Engng. Educ.*, 14, **1**, 6-13 (2012).
8. Graves, G., The magic of metaballs. *Computer Graphics World*, 27-32 (1993).
9. Schroeder, D., Coffey, D. and Keefe, D., Drawing with the flow: a sketch-based interface for illustrative visualization of 2d vector fields. *Proc. Sketch Based Interfaces and Modeling,* Annecy, France (2010).