Introducing Robotics to Students Through Novel Architectural Fabrication

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ABSTRACT: *In spring 2021, a research-based graduate robotics studio was developed. The question posed to the students was: how robotic construction can facilitate new and innovative architectural construction methods? Each student was tasked with developing a new construction workflow using a custom-designed tool or end-effector attached to the end of a robotic arm. Robotic arms enable and encourage the use and creation of custom end-effectors or tools to create new manufacturing methods. The development of new end-effectors and construction workflows allows for greater customization and variability of the fabricated outputs. The studio began with an examination of the field of architectural robotics. This was facilitated through a preliminary precedent study where the students were asked to document ten conference papers through a brief description of their relevance, how the investigation could be expanded, as well as their associated images and diagrams. This study aided in the student's understanding of what is possible in addition to the common materials and end-effectors used in robotic fabrication. The goal was to narrow their focus and cultivate a novel research question. In conjunction with this study, the students were tasked with small robotic fabrication projects to understand how to develop a toolpath for the robotic arm to follow using McNeel's Grasshopper and the plugin KUKA|prc. The students spent four weeks of the semester working on their custom tool and fabrication process. These tests were documented with videos, photographs, and written observations. This allowed each student to create small mock-ups of their projects before refining and creating the final full-scale projects. These new construction workflows looked for ways to limit waste, expedite fabrication processes, and generate customization with purpose. The students' work investigated robotic clay 3D printing, aluminum embossing, and sewn fabric as means for concrete formwork and thermoforming informed by computational fluid dynamics (CFD) to generate optimized acrylic panels that control airflow. Each student was asked to document their projects with a 600-word academic research paper with a minimum of five figures explaining a novel process. When the semester began, the students had no experience with fabrication or robotics. When the studio concluded, all felt comfortable using the machinery independently. This paper will provide an overview of the course, and its assignments, discuss the students' resulting work, and reflect on the course and what was learned.*

KEYWORDS: Robotics, Digital Fabrication, Formwork, Additive Manufacturing, Design-Build

INTRODUCTION

Computational design and digital fabrication technologies have become a distinct force within contemporary architecture. The translation from digital to fabricated objects is enabled by a wide range of tools and processes, such as computer numerically controlled (CNC) milling and 3D printing. The tools have been further democratized concerning accessibility and affordability within the last 15 years. These processes have altered how buildings are envisioned and constructed. It has allowed designers to engage with manufacturing and materials in new ways, allowing new opportunities and challenges in realizing architectural elements (Dunn, 2012).

Robotic fabrication permits greater flexibility with double the axes provided by a standard cartesian CNC machine. Robots enable and encourage the use and creation of custom tools or end-effectors to create new manufacturing methods. The development of new end-effectors and fabrication workflows allows for greater customization and variability of the fabricated outputs. Robotic fabrication courses tend to be cloistered within specific programs with an emphasis on this niche and at highly funded institutions. The outcomes of these student projects are the focus of their publication rather than their pedagogy. Therefore, documentation of proposed teaching methods for the integration of these tools into the architectural curriculum is needed.

Large firms such as Perkins and Will, Kieran Timberlake, Corgan, and SOM have integrated design research into their practices (Davis, 2015). When Huckabee College of Architecture (HCoA) alums are asked how faculty can best prepare students to join their firms, most ask that the students are able to conduct research. The National Architectural Accrediting Board, Inc. (NAAB) has emphasized research and innovation in its 2020 Conditions and Procedures for Accreditation. Placing significance on how the curriculum prepares students to innovate through engagement and participation in architectural research.

This paper will discuss a second-year graduate research-based option studio that introduced architectural robotic fabrication to the students. Before this studio, the students had little knowledge of computational design and digital fabrication. None of the students had ever used a robotic arm. This was the first-time robotic arms were integrated into a course at the HCoA. Therefore, the final project brief was open-ended to allow the outcomes to be altered, if necessary, during the semester. This paper will discuss the organization of the course, review student work, reflect on the course, and how it might inform future teaching.

1. METHODS

1.1 Course overview

This studio was offered as part of the design, computation, and fabrication (DCF) certificate at the HCoA. This certificate program allows Master of Architecture (MArch) students to have a specific focus. The DCF students are required to take a research-based studio in their final year of the two-year program that emphasizes their certificate niche. The studio discussed in this paper filled that criterion. In addition to this studio, the students must take additional courses within this specialty to fulfill the certificate. It met three days per week for four hours in the college's robotics lab. The faculty's research funding covered almost all the fabrication costs.

1.3 Studio assignments

This was the first course in which the students engaged with robotic arms. Therefore, the class began by introducing the equipment and this architecture area to the students. As knowledge and confidence were gained, the assigned tasks increased in complexity. The overarching project for the semester was the development of a novel fabrication workflow using a custom-designed end-effector or tool that could attach to a KUKA KR10 sixx or a KUKA KR120 QUANTEC. The end-effector could be created using 3D printing, CNC routing, laser cutting, or other fabrication methods. It might also utilize off-the-shelf hardware or electronic components. The robotic arm with this custom end-effector could perform fabrication tasks such as embossing, carving, marking, etc. The fabrication investigations were iterative, meaning the students produced multiple versions of their end-effectors to refine the design and fabrication workflow. The iterations were documented with videos, photographs, and written observations. The students were encouraged to consider workflows with limited waste, expedited fabrication processes, and create purposeful customization. The students were required to develop a research paper to document the final project.

Review of Literature

The studio began with a three-week examination into the field of architectural robotics. This was facilitated through a preliminary study where the students were introduced to CumInCAD, a website housing a cumulative index for the many computational design and digital fabrication in architecture publications. First, each student was asked to document ten conference papers by briefly describing their relevance, how the investigation could be expanded, and their associated images and diagrams. This study aided in the student's understanding of what was possible in addition to the common materials and tools used in robotic fabrication. In the second round of the review, the students were encouraged to narrow their focus to a specific material or workflow they would be interested in pursuing in their final project. The goal was for the student to understand the work being done and ask how it could be expanded in their project so they could start developing their research questions. The students presented each literature review to their peers during class, which allowed the students to see a higher quantity of research projects collectively. It also allowed the students to see what other students were interested in and provoked conversation.

Robotic Workouts

On the first day of class, the students were given a robotics tutorial. First, a presentation was shown that discussed the various axes, and the digital workflow, and showed some precedents. The students were taught how to operate the robotic arms by jogging each of the six-axis and also how to jog the arm in cartesian mode. A 3D-printed tool was placed on the end of the robotic arm, that's shape was a cylinder with a cone at the end. This same tool was placed in various locations in the robotic arms workspace. The goal was that the students move the arm so that the tool on the end of the arm and the tool within the workspace was touching. This allowed the students to get familiar with changing the speed, the various movement types, and the pendant (the tablet used to control the robotic arm). Since there were only two robotic arms, this provided the students with an icebreaker and a fun way to learn how to use the equipment. An additional two short robotic fabrication workouts were assigned over the first three weeks of the studio. These short workouts allowed them to understand how to operate the robotic arm to perform a specific task. The first workout was milling foam with an integrated spindle. The second was wire cutting a piece of foam. This aided in the students' understanding of the digital workflow, assisting them in learning how to create toolpath files for the robotic arms using McNeel's Grasshopper with the plugin KUKA|prc. These fabrication workouts were archived through the creation of a portfolio documenting the fabrication process, the result, and a short summary of what they learned.

Electronics Assignments
The students were introduced to electronics during the first four weeks using the Arduino Project Book (Fitzgerald, 2012). Each student was provided with a small starter kit and worked through each chapter. The goal of this assignment was for the students to engage with electronics in their robotic end-effector designs. These assignments were completed outside of studio time and were documented through a portfolio submission where the students took photos of the created circuits and wrote a brief summary of what was learned.

Preliminary Material and Fabrication Testing
During the third and fourth weeks of the studio, using the inspiration from their literature review, students started selecting materials and fabrication methods. These materials were explored through small mockups. The tests were rudimentary and quick studies focusing on understanding what might be possible and the potential limitations of the selected material. Many students tried to recreate work that had been investigated within their literature review. One tested the ability of various 3D-printed plastics to withstand heat and act as an impression device for heated acrylic. Another tested various fabric formwork techniques. During this period, they were encouraged to start considering how they could build off the precedent research projects and add a new, innovative contribution. Additionally, they were asked to consider how the small mockups could be translated into robotic fabrication processes.

End-Effector Design and Fabrication Development
The students spent around eight weeks developing their custom end effectors. No student had a fully functional end-effector on their first attempt. Each created at least two more iterations resolving design flaws. Depending on the task they were asking the robotic arm to perform, some end effectors would break under pressure or prove unsuitable for the desired objective. This refinement allowed the students to test a variety of materials and methods of fabrication.

The students were asked to physically act out the tasks they were requesting the robotic arms to perform and then write each step chronologically. This process would help the students to understand better how they might develop a toolpath for the robotic arm. Since the students were new to robotics, Grasshopper, and the plugin KUKA|prc, the instructor and the student would develop these initial toolpath files together. As confidence and knowledge grew, the students started to be able to modify the definitions alone. Additionally, when students ran new toolpaths on the robotic arm, the instructor was present to monitor and assist if modifications to the robotic program were needed.

The development of the end-effector and the small fabrication tests started to provoke ideas for their final full-scale fabrication projects. The viability of the final end-effectors and the fabrication methods were tested through the development of a final fabricated output during the last 3-4 weeks of the semester. These ranged from a 3 ft wide vault to a 10ft x 4.5 ft wall. The student work will be further discussed in the Results.

Research Papers
The students developed 600-word academic research papers. Through lectures, the students were introduced to writing an academic research paper. The initial review of the literature helped the students in the development of their introduction, allowing them to specify how their research project and fabrication workflow was new, innovative research building on prior work with similar materials and methods. The archiving of their design iterations allowed the methods section of their papers to be well documented. The written reflections that the students kept while working through their end-effector designs and the fabrication of their final projects allowed them to recall specific issues they had along the way so they could better articulate the struggles in the discussion and results section of their paper. The students also received a final review prior to their paper's due date, which allowed them to start considering how the work could be expanded or further resolved to aid in the creation of their conclusion.

2. RESULTS
Four examples of student projects completed in this studio will be discussed in this section of the paper. These new construction workflows looked for ways to limit waste, expedite fabrication processes, and generate customization with purpose. The students' work investigated thermoforming informed by computational fluid dynamics (CFD) to generate optimized acrylic panels that control airflow, sewn fabric as means for concrete formwork, aluminum embossing, and clay extrusion.

2.1 AirForms
Robotic thermoforming has been utilized in multiple published works. It often relied on the robot holding and pushing a tool into a heated polymer held at its edges by a rigid frame (Tian, et al., 2017; Zhu, et al., 2021). This student's research focused on manipulating two edge conditions, not solely the center of the polymer.

Instead of pushing the entire tool into the material, this student leveraged the curvature of a 3D-printed ellipsoidal design to create varied edge conditions on each panel.

This fabrication began by hovering an acrylic panel over a heat gun until it was malleable. This was completed by developing a rectangular frame as the robotic end-effector that held a single 6-inch square of 1/8-inch acrylic. Depending on the panel design, the time and distance over the heat varied to allow differing levels of plasticity. These parameters and limitations were documented throughout the development of the fabrication process. After the heat was applied, the acrylic was moved to the proper position and pressed at a specific depth into a 3D-printed impression device allowing for the manipulation of the edge profile of the panel (Fig. 1). Thirty panels were created to test the system's feasibility as a façade. Each row was given a specific wind direction and speed, which informed the panel designs (Fig. 2). Autodesk CFD simulated wind movement and informed each panel's designs. This allowed the digital designs to be tested. The wind is controlled and directed in specific ways based on the panel's curvature, which could allow for prevalent local winds to be considered and inform panel designs. Considering the proposed fabrication method's flexibility, this could allow for custom façade designs to be informed by specific site requirements and climates.

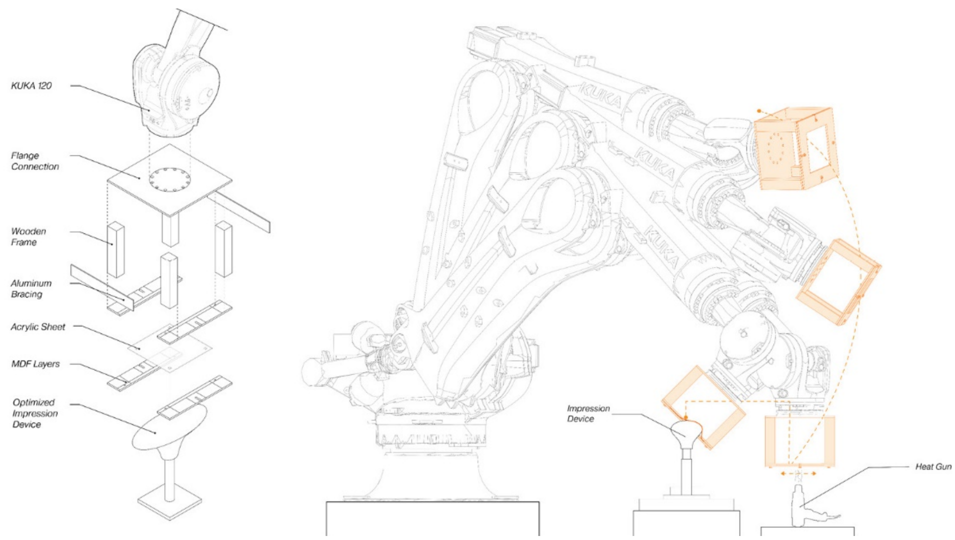

Figure 1: The drawing on the left shows the student's end-effector design and the 3D-printed impression device. The diagram at the right denotes the robotic workflow—work by Mark Eisenmann. Source: (Mark Eisenmann 2022)

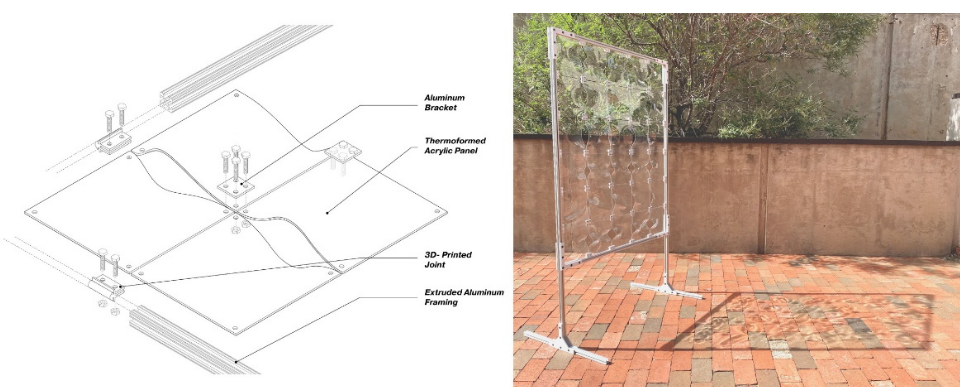

Figure 2: The drawing on the left shows the custom components designed to hold the panels. The image at right shows the completed 30 panels housed in a custom frame. Work by Mark Eisenmann. Source: (Work by Mark Eisenmann 2022)

2.1 Formwork waste

A reoccurring theme in the student projects was concrete formwork which is the instructor's area of research focus. Each project considered formwork waste differently but attempted to limit it as much as possible. The construction industry contributes around 35% of solid waste produced globally and annually (Llatas, 2011). The creation of concrete structures has contributed significantly to this problem since single-use formworks are often needed to cast concrete. Globally, the number of concrete construction projects continues to increase (Leder, 2020).

2.2 Robotically assisted reconfigurable fabric formwork

Fabric formwork has been investigated in architectural fabrication due to its low material use and versatility. Previous fabric formwork investigations have utilized rigid structures with reconfigurable components and single-use formwork (West, 2016; Kudless, 2011). The MARS pavilion combined the precision of robotic movement to orient fabric formwork to create seventy unique casts to construct a pavilion (Sarafin, et al., 2017).

This research project investigated the creation of an efficient, reconfigurable, and reusable robotically assisted fabric formwork system for casting. This proposed system utilized a single reusable fabric hexagonal unit 6 in long and 2 in wide, tapering at the center. The tapering was to prevent the bulging of the cast material at the center. A custom robotic end-effector was designed to hold the formwork for casting. Through the precise placement of the robotic arm, unique designs can be obtained. The same fabric formwork can be repeated and reused throughout the project as it increases in scale and complexity (Fig. 3).

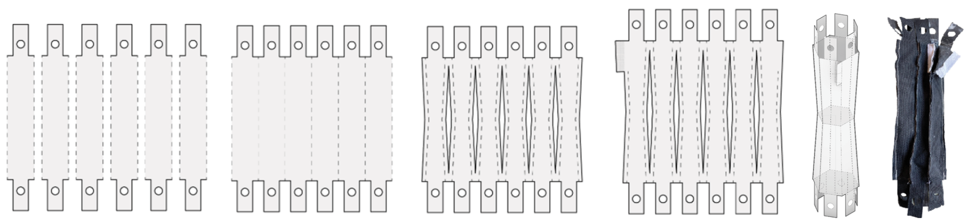

Figure 3: A- D are the fabric formwork designs that were explored. Design D, the final design, is denoted in an isometric drawing (E) and an image of the formwork (F). This formwork was used six times and showed minor wear. Work by Mohammad Karkoutly. Source: (Mohammad Karkoutly 2022)

A variety of fabrics were investigated. Aggregation of a single formwork unit was developed. Bipod and tripod iterations were achieved by adding VELCRO® strips that allowed the formworks to be combined by providing a sufficient material connection. A column was created over two days to test this fabrication system's viability (Fig. 4). It was chosen to highlight the versatility of the formwork system. This system allows for infinite design variations.

Figure 4: This image shows the process of pouring Rockite (A), placing all thread reinforcement immediately after casting (B), and leaving the material to cure (C). The bottom images represent the casting of the layers using the robotic arm (D and E) and the final column design without the base and the bottom formwork removed (F). Work by Mohammad Karkoutly. Source: (Mohammad Karkoutly 2022)

2.3 Reconfigurable embossed aluminum formwork

This work builds on robotic incremental metal forming explored extensively in the last decade (Hong-Fen, et al., 2019; Qiang, et al., 2022) in conjunction with concrete casting to produce prefabricated concrete panels. It embraces the qualities of thin (0.0019 in) aluminum sheets through their ability to retain patterns, be contorted into doubly curved forms, and their durability. This panel fabrication method allows for various novel designs and utilizes limited, reusable formwork through a constrained kit of parts.

This student project investigated a method to reuse highly customizable formwork. The proposed formwork system uses robotically embossed aluminum sheets with custom-milled formwork assembled with off-the-shelf hardware. A wall of eighteen bespoke panels was created to test the viability of the fabrication method. It was designed as a sinusoidal wall, each row tapering in thickness, to allow greater structural integrity. A seamless pattern was chosen to allow for greater versatility and reconfigurability. Eight aluminum panels were created with four pattern designs and their mirrored versions. Two of the eight metal sheets would be used for each cast, one on either side of the routed components to create the formwork (Fig. 5). The panels connect with welded joints to create a structure without additional support (Fig. 6). The use of metal sheets allows for infinite patterns to be embossed. The ability to reuse the metal sheets for multiple casts was key since their reconfigurability allowed the patterns to be used in various ways regardless of orientation.

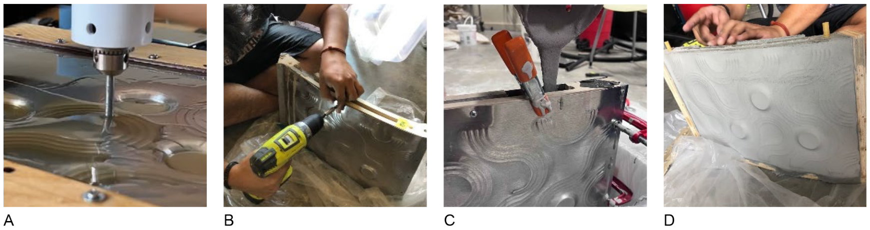

Figure 5: The robot embossing the aluminum sheet using a 3D-printed end-effector holding a drill press chuck with a rounded metal rod (A), Assembling the formwork (B), casting (C), and formwork removal (D). Work by Adrian Reyna. Source: (Adrian Reyna 2022)

Figure 6: Image A shows the hole left within the cast for the welded connection (B). This welded component holds the tiles together. Photo C shows the final wall—work by Adrian Reyna. Source: (Adrian Reyna 2022)

2.4 Modular and reconfigurable paper clay formwork

This project deviated from the brief. While it was computationally derived and digitally fabricated, the student strongly desired to 3D print in clay. Instead of re-creating an end-effector, the student used an existing clay 3D printer. The work focused on combining 3D printing and conventional hand-building of unfired clay to leverage each strength in creating custom, zero-waste, reusable formwork.

The fabrication method relied on the plasticity and water-solubility of clay in an unfired state to permit the production of larger, more complex clay formwork. This is achieved by aggregating 3D-printed units with hand joinery (Fig. 7). Since unfired clay possesses limited strength and struggles to hold its weight, shredded paper was introduced. After casting, the paper clay can be removed, rehydrated, and recycled to create additional 3D-printed formwork.

The same design was printed to test the compressive strength of 15%, 25%, and 35% paper-to-clay ratios. The test concluded that these additions successfully reduced the clay's weight while increasing its load capacity. The first two fabrication tests used small units (1 in x 1 in x 2 in). The first was tessellated into an arch using hexagonal prisms. This tested the feasibility of the unit bottom used for joinery and the top holding the casting material. The second iteration assessed the possibilities of custom patterning through toolpath manipulation. The final test increased the scale of the units (6.45 in x 5.75 in x 5 in), resulting in a three-foot-wide dome (Fig. 8). Fifty-four units were printed, then stored in a container to avoid significant drying. The cast was successful without formwork failure. The clay was removed and reused.

Figure 7: This series of images shows the joinery process of the 3D-printed units. Scoring the clay (A), applying slip (B), connecting to other units (C), applying pressure (D) The tessellated units resting on a bag of paper for support (E)—work by Haley Arthur Eisenmann. (Haley Arthur Eisenmann 2022)

A B C D E F

Figure 8: Image A shows the 52 units. The plastic keeps them from drying further as they are assembled. A diagram denoting the assembly logic can be seen in Image A. Image B shows the students constructing the formwork, and Image C shows the additional clay added to prevent leaking. Image D shows students removing the clay formwork. The clay is beginning to dry and fall off in image E. The final cast is displayed in image F. Work by Haley Arthur Eisenmann. (Haley Arthur Eisenmann 2022)

3. DISCUSSION

Now that the studio has completed its first iteration, there are a number of things that could be refined and further developed if it were to be taught again. This section will reflect on the course.

It was noted that too much time was spent on the initial robotic assignments. Dropping one of the first introductory robotic assignments, which took place over the first month of the semester, could increase the final project fabrication time, which was too short. It was noted that students who engaged with the robotic arms learned substantially more about its operation through the design of their novel processes. When the semester began, they could not create a tool path for or operate the arm on their own. After a couple of weeks of working on their projects, they gained confidence and an understanding of its workflow. The only criticism within the student evaluations was the studio's pacing. This was a direct result of the majority of the final project fabrication taking place in the last two weeks of the course. The students felt it required additional time. It might be best in future iterations of the course to have the students work in pairs rather than individually. The workload proved to be too extensive for a single student. While some students were excited to spend a lot of time refining and redeveloping their projects, other students found it frustrating and too time-consuming as a result, the final projects varied in quality. The four discussed in the paper were the most successful of the seven proposals. The other three needed additional iterations and more time to be developed further. Additionally, it would be easier to mentor and technically assist with half the number of projects.

The assignments throughout the semester could be refined and provide more guidance to the students. It would be helpful to have an outline instructing the students on how to compose a research paper. Contemplating the studio's structure, it could be possible to break the paper into manageable parts, executing various sections chronologically in conjunction with the assignment briefs. This would assist in student reflection throughout the course of the semester. Most students were able to use the research projects referenced within their preliminary literature review to help in the writing of their papers. Although, many had found additional references that they added to their review throughout the semester. No student elected to use electronics in the creation of their end-effector or to augment their final project. This has resulted in the questioning of the inclusion of the Arduino Projects Book assignment. The use of electronics could be integrated without such an assignment based on the need of each student project.

One of the great successes of the studio was the bond between the entire cohort. The students were always talking to each other and trying to help others develop their projects. The students would offer advice and share what they had learned with others. This was very evident at the end of the semester when the students were fabricating their final models. There was much collaboration and support between the students. They helped each other cast and construct their final models. This created pride in not only their own work but that of their classmates. This can be seen in Figure 8, where all students are assisting in the assembly of the clay final clay formwork. Since the students picked such varied approaches and materials, it was sometimes difficult for students to learn from one another. The one throughline throughout nearly all the projects was the integration of casting. This allowed the students to learn from the other formwork systems. In future iterations of the course, it might be beneficial to limit the material or fabrication task to casting or something that allows the student projects to be more connected so that there could be more shared learning from project to project. Overall, the studio was a success and was reviewed highly by the students who participated.

CONCLUSION

This studio was developed to allow the students an opportunity to investigate how robots can be integrated into construction practices and aid in the development of new fabrication workflows. Each student developed a project, and all but one utilized robotic fabrication. The students ended the course with an understanding of the field of architectural robotics. By the conclusion of the studio, all students felt comfortable operating the robotic arms and creating their toolpaths with the Grasshopper plugin KUKA|prc. The students further engaged with fabrication through the creation of their custom end-effectors using 3D printing, laser cutting, and off-the-shelf hardware. They created iterative variations of their projects, starting at a small scale and then moving to full-scale fabrication. The projects focused on limiting waste and expediting fabrication processes. Each student generated a project that used purposeful customization. This studio provided the students with a greater understanding of digital fabrication methods and the future possibilities of these tools.

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