Towards Technically Progressive and Speculative Design Education: Penn MSD-RAS's Collaborative and Interdisciplinary Pedagogy

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Transformative societal and industry changes in the architecture and construction industries are afoot with the rise of the Fourth Industrial Revolution that warrant further consideration within architectural education. To address this, the Masters of Science in Design: Robotics and Autonomous Systems program (MSD-RAS) at the University of Pennsylvania's Weitzman School of Design is exploring a hyper-collaborative pedagogy that places greater emphasis on the synthesis of knowledge across all courses rather than on a design-led studio course, while integrating advanced technical knowledge. It is hoped the pedagogical approach fosters novel and exploratory work while supporting a more diverse group of students and career trajectories for graduates. This paper explores some key aspects of the pedagogy that will be expanded on in an upcoming book that covers activities from the first three years of the program.

EDUCATION AND INDUSTRY 4.0

Higher Education aims to equip students with the knowledge and skills to empower them to have successful careers that span from the present to decades into the future. This is challenging when socio-economic and technological changes rapidly transform the world graduates operate in, and corresponding career prospects (some architects who graduated at the beginning of the twentieth century after the Wright Brother's first successful flight might have practised long enough to witness the first orbiting satellite or moon landing). How do we equip students for the unknown? Educational institutions can commence by addressing present and emerging technological and industrial trajectories, and by operating both practically and speculatively in parallel.

At this critical junction at the commencement of the Fourth Industrial Revolution (IR4.0), there is growing consensus that rapid developments in robotics, artificial intelligence and material science are facilitating the emergence of autonomous manufacturing, where economically scalable approaches to distributed manufacturing on-demand, user-customization, and locally sourced or produced materials become more possible[1]. Coupled with cyber-physical systems, there is the potential for a more direct engagement between the built environment's inhabitants, designers and manufacturers. While these technologies offer untold possibilities, they also threaten to increase inequity, consumption, and waste. The growing use of machine learning and other forms of software automation also increasingly challenge established roles within architectural practice. It seems imperative that architectural education must leverage these developments to increase the architect's agency, and to address pertinent issues such as building affordability, resource and infrastructure equity, environmental impact and more. To achieve this, more technological engagement is needed. Inspiration can be found in the technology sector, where novel developments and start-ups are often closely aligned to or seeded from scientific or engineering academic activities. In contrast, the vocational education of architecture is less well-equipped to address technological changes in industry and practice and has not grappled with the radical changes IR4.0 might instigate. Research-led design programs provide one means to address these concerns.

EDUCATIONAL CONTEXT

Architectural professional degree programs are centered on project-orientated work stemming from eighteenth-century France's L'Ecole des Beaux Arts educational model[2]. As Allen Cunningham describes, the Beaux Arts system placed primacy on the design project, undertaken within an "atelier" run by an experienced "patron" architect[3]. According to American academic and former President of the Association of Collegiate Schools of Architecture (ACSA), Rashida Ng, the Beaux Arts model most American architectural programs operate under is insular in nature and designed to cater for a historical, elitist, wealthy, white male student. She argues that radical changes should be implemented in architectural pedagogy to support more collaborative, open dialogue that is inclusive of all students, and recognizes students' diverse backgrounds – be these racial, gender, sexual orientation, social or economic in nature[4]. Professor Ng also suggests that the primacy of "design" leaves little room for students to foster other aspects of their architectural education that could lead to more diverse career opportunities[5].

Figure 1. Ceramic multi-part assemblage prototype produced by students during the last semester of the MSD-RAS program. MSD-RAS 2020-1 Spring Semester Project "Robotic Prometheus"

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While changes must be made to professional degree programs, post-professional Masters and PhD programs do offer opportunities for students to engage in more diverse subject areas and build more career opportunities through the attainment of research-orientated knowledge and skill specialization. Some are also recognized as STEM certified, acknowledging the role of science, technology, engineering and mathematics within their curricula[6]. In the Weitzman School of Design's Department of Architecture, a series of STEM-certified post-professional Masters of Science in Design (MSD) programs offers graduates from professional degrees opportunities to specialize in one of a number of different knowledge streams. The most recent addition to these, the MSD-RAS focuses on the integration of robotic fabrication and computation within design. The MSD-RAS, aims to fill an education gap, where state-of-the-art robotics, fabrication, computation and design knowledge can add value to the field of architecture by training and empowering graduates to make an impact in industry, practice and academic research. With this ambitious remit, the pedagogical structure of the MSD-RAS program offers an alternative to established models of design-research to support diverse, specialized career trajectories.

DESIGN-RESEARCH MODELS

The term "design research" is loosely defined in architectural education. It is used to describe professional degree design studio project formulation activities alongside more scholarly history and theory research in doctoral studies[7]. The MSD-RAS operates similarly to scientific and engineering research models employed in more technically orientated research-led doctoral design activities such as Harvard GSD's DDes program[8], ETHZ's Gramazio + Kohler Research Lab[9] and others. However, these PhD programs prioritize individual specialization over the more collaborative research frameworks explored in post-professional Masters degrees. Cornell's MSc Matter Design Computation program[10], University of Stuttgart's ICD program[11], and the Architectural Association's Design Research Laboratory[12] and Emergent Technologies programs[13], offer curricula that support students working in groups on a design-research project. While extremely successful, the degree to which these models mirror interdisciplinary, collaborative work approaches found outside academia is difficult to evaluate. With courses outside of the design thesis project typically relegated to pre-requisite or adjacent activity status, the relationships these programs forge between different curricula could be expanded, suggesting there are opportunities to explore alternative educational models.

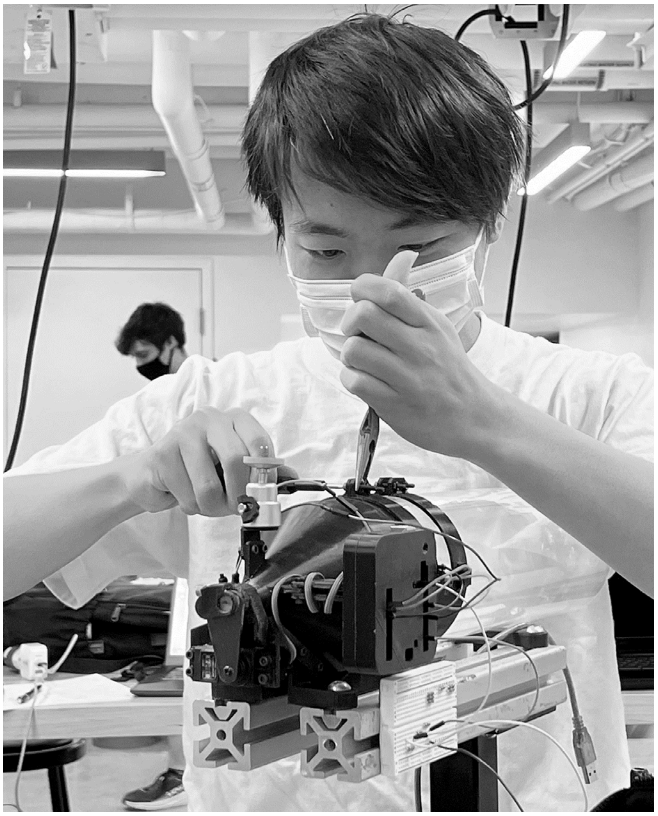

Figure 2. MSD-RAS students contribute creative and technical knowledge to their final thesis project that is supported across four concurrent courses. Photo by Robert Stuart-Smith

AN ALTERNATIVE PEDAGOGICAL APPROACH

The two-semester-long MSD-RAS program includes three design studios that primarily operate through the development of experimental fabricated prototypes. Each studio explores a different material and fabrication approach that varies over time. Each studio's design brief is also light on professional degree architectural criteria (such as planning, site, etc) in order to focus activities on core knowledge domains aligned with the program's specialization in robotic fabrication and computational design. The first two half-semester length studios in the Fall semester are more tightly choreographed in design and manufacturing workflows, operating more as design workshops that expose students to a diversity of design and manufacturing methods.

In the final spring semester-long studio, an integrated approach to curricula is explored. A research-led design thesis project is undertaken across four courses concurrently, including scientific research and writing, industrial robotics and tooling, advanced robot programming, and a design course that emphasizes research-led experimentation and the production of robotically fabricated physical prototypes. Given the MSD-RAS program's technical and hands-on curricula, a pedagogical structure was developed that aimed to support an integrative and collaborative approach to design-research, premised on the following.

I. All coursework matters equally (in contrast to the Beaux-Arts prioritization of design), and therefore all courses should form part of final thesis projects.

II. The implementation of (I) provides students with more agency to weight their project towards subject areas of personal interest and aims to facilitate more diverse career opportunities post-graduation.

III. Application of coursework in design-fabrication work supports learning by re-enforcing attained knowledge through hands-on experience.

IV. A speculative component in assignments encourages exploratory work beyond the pragmatics of (III).

V. Undertaking research on even one aspect of a design's life cycle (such as fabrication or disassembly) can be transformative and lead to novel design opportunities. Research can be focused.

VI. Despite (V), a project will require engaging with disparate courses' subject matter concurrently, potentially leading to more novel, accomplished and integrated design work.

VII. Developing a project along several lines of inquiry at once is more easily achieved by teams than by individuals.

VIII. To support the above, ideally, faculty from all courses participate in group thesis project formulation, review and assessment, and bring diverse, complimentary specializations to the curricula.

IX. Research-led design can commence with a literature review exercise and the positioning of design-research activities towards a novel academic contribution.

X. Dissemination of research-led design outcomes both contributes knowledge and connects graduates to the broader academic research community, encouraging dialogue and collective learning.

In the first year, final semester courses ran in parallel with coordination between instructors, however, outside of individual course schedules, students only met with the instructors all together at mid-term and final reviews. In the second and third years of the program, all course instructors met students together at four intervals throughout the semester to review initial thesis proposals right through to project realization and write-up activities.

DESIGN-RESEARCH PROJECT BRIEF

In the final semester of the program, individual student teams develop a research-led design thesis project that synthesizes four courses teaching and guidance, developing a creative and critical research around industrial processes of manufacturing, robotic fabrication and design computation. This research is primarily focused on the development of a design-to-production workflow that is explored and demonstrated through physical prototyping, computer modelling, simulation and design visualizations and communicated in a research paper and thesis

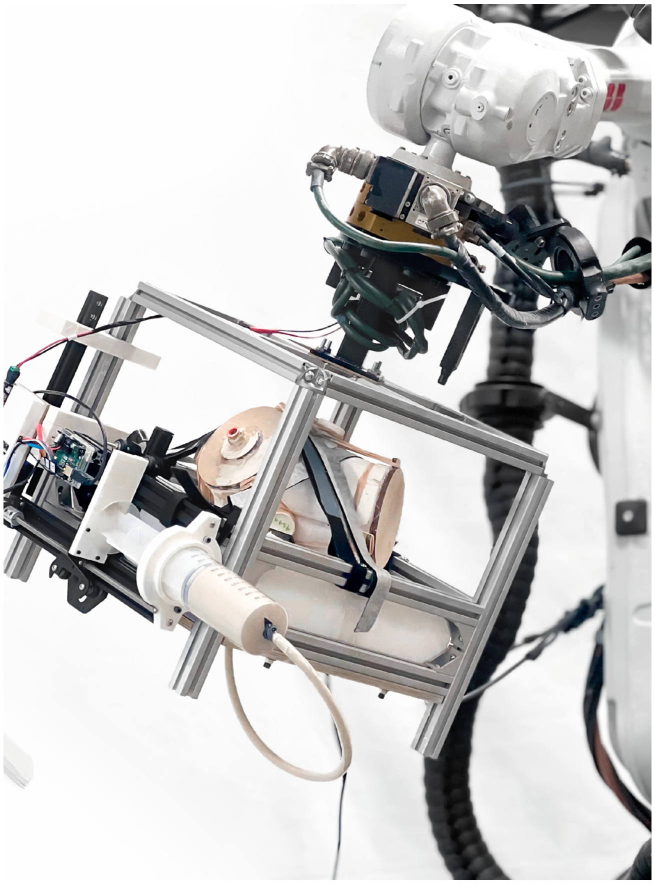

Figure 3. Custom robot end-effector tool. MSD-RAS 2022-3 Spring Semester Project "Dynamic Slip-Casting".

Figure 4. Ceramic multi-part assemblage prototype . MSD-RAS 2022-3 Spring Semester Project "Dynamic Slip-Casting".

book. Successful design outcomes are intrinsic to this bespoke production workflow. Individual student teams develop a thesis in response to a shared topic that is envisaged to change every three years, allowing for a collective body of knowledge to be explored that builds on previous years of experience. The first three years of the program explored architectural ceramic assemblies, with a focus on façade screens. Students produced a full-scale multi-part assembled prototype together with a concept design for a building-scale façade-screen. These projects originated from research-led experiments in robotic fabrication and integrated approaches to design.

While bespoke methods are frequently used in ceramic art to produce widely varied works, undertaking ceramic production at the scale of buildings and building component parts poses additional challenges that make bespoke work difficult to implement, particularly in terms of time, cost, and waste efficiencies. Industry-prevalent Fordist production methods meet these challenges through the repetitive use of molds, jigs, etc., that enable substantial returns on investments through the production of numerous identical parts. Robotic platforms, however, enable the automation of bespoke manufacturing. While fabricating unique parts with a programmable machine might seem to add almost no additional cost, this is not necessarily true, and great consideration must be undertaken by students in evaluating and developing a production workflow. Processes that enable greater efficiency and complexity while remaining more economical are encouraged as these not only offer environmental benefits, but are also more likely to gain industry traction in addition to offering exciting creative design possibilities.

Working in teams, students commence with literature review to gain an understanding of state-of-the-art academic research and industrial practices before identifying a design-research topic that works with a specific ceramic manufacturing process (E.g. extrusion, pressing, slumping, additive manufacturing, slip-casting, die-cutting, wheel-throwing/jiggering, sculpting/carving, deforming, glazing, etc). Physical tests are then undertaken to establish possible avenues for augmenting the manufacturing method through a robotic process. Speculating on the potential for robotic fabrication to facilitate a more bespoke architecture, each team also defined specific design considerations that their façade screen could incorporate (E.g. functional, environmental, material, and ornamental agencies of the design), and attempts to resolve these within a design approach that emerges through the development of a novel means of robotic production. A design methodology is developed that integrates aspects of their manufacturing process from the outset, alleviating the need for

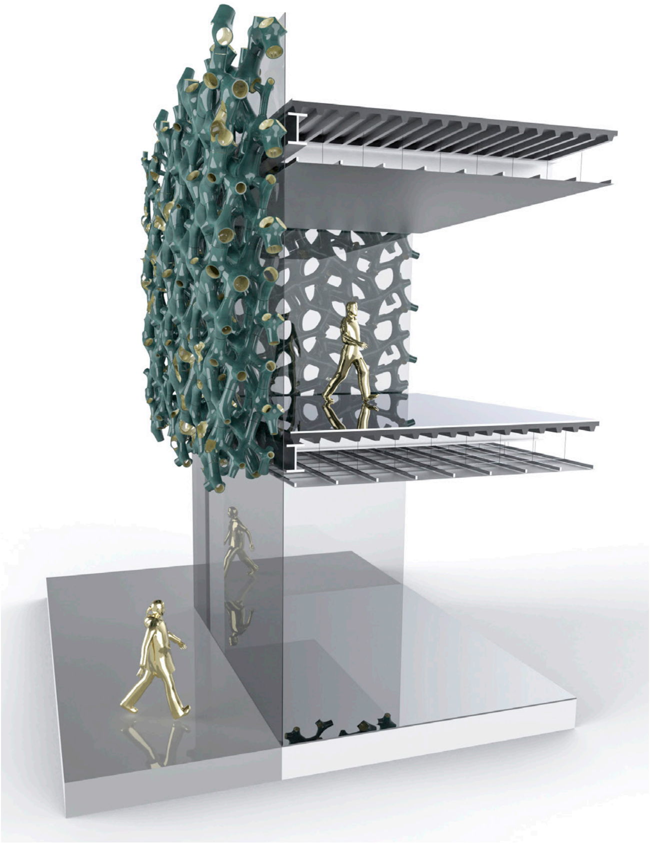

Figure 5. 3D chunk section through prototypical building facade screen design. MSD-RAS 2022-3 Spring Semester Project “Dynamic Slip-Casting”.

industry practices such as geometrical rationalization or value-engineering exercises. Design-research projects are undertaken within a sixteen-week semester from inception to completion, with each project demonstrated through a robotically fabricated prototypical assemblage, a research paper and a project thesis book that documents their literature review, research experiments, production process, and corresponding speculative design proposal.

PROJECT OUTCOMES

Projects successfully developed a novel robotic manufacturing approach to ceramic façade part fabrication and corresponding design methodologies that were also applied to a prototypical façade screen design. Beyond solely developing a custom manufacturing workflow, student teams managed to apply the research within a short and intensive robotic production timeframe to produce a large number of parts for a full-scale multi-part prototypical assemblage, demonstrating the merits of their approach. Across the three years, all of the research outcomes were of high quality and interest. To adhere to the word count limits of this peer-reviewed paper submission, only three examples are provided that are representative of these projects. The examples all leveraged industrial robot motion to dynamically engage in a formative material process.

Dynamic Slip-Casting: Slip-casting is a manufacturing method that can make complex and thin-cast ceramic parts of outstanding quality. Clay slip is poured into a mold (typically plaster) where a cake of clay dries rapidly on the interior surface of the mold as water is absorbed into the mold, resulting in a hollow, thin-shell ceramic part. Due to the reliance on molds, slip-casting is more often used for sanitary ware and other mass-produced parts rather than for facades that typically require several parts of different dimensions. Façade designs also frequently utilize vastly differentiated proportions and part sizes to accommodate varied site, interior or aesthetic conditions that would not be economically or environmentally feasible to undertake by small-batch production using a large number of molds. To address this, the Dynamic Slip-Casting project develops a large number of geometrically varied slip-casts from a single mold. Extending a previous MSD-RAS project’s exploration of slip casting by robotic roto-molding that produced variations in slip color within individual parts[14], a custom approach to slip-casting was developed that leverages custom robot motion routines to swish around a partially filled mold with timed micro-dosing of slip. A computer simulation model of the approach was also developed and validated by comparing simulation outcomes to scanned manufactured parts. A full-scale prototypical assemblage incorporates twenty-eight different parts produced using only four different mold geometries. The research is complemented by a digital design that utilizes the simulation to generate part geometries applied in larger quantities to a building façade screen.

Steamed Greens: Steamed Greens explores the use of urban steam waste to irrigate green walls in pop-up public gardens in underutilized, residual urban spaces. A computational design method defines a branching façade system that connects existing blank vertical wall areas of varied solar exposure to urban steam vent locations. A ceramic wall system was devised that combines two formed panels into a sealed unit that incorporates branching tubular voids capable of transporting steam, while small holes in its surface enable steam to pass through the ceramic to condense on its outer surface where it serves to irrigate plants. The wall system’s panels are shaped using a custom-developed ceramic incremental forming process that involves a passive re-usable mold and a ball-roller forming tool that manipulates a flat slab of clay into a three-dimensional shape[15]. The custom tool reduces friction in the clay to prevent tearing during the forming process. A final part’s geometry is arrived at through iterative forming with 3D scan feedback in-the-loop. The zero-waste method develops variably-formed parts without necessitating custom molding or clay offcuts.

Robotic Prometheus: A third project proposes a multi-species façade screen. In addition to providing privacy and shade to a building’s human occupants, the project aims to reduce bird strikes by partially obstructing reflective glass facades while

Figure 6. Ceramic multi-part assemblage prototype. MSD-RAS 2020-1 Spring Semester Project "Steamed Greens".

Figure 7 (Top). Ceramic incremental forming method with custom roller-ball tool.
Figure 8 (Bottom). Ceramic green wall irrigated by urban steam waste. MSD-RAS 2020-1 Spring Semester Project "Steamed Greens".

also incorporating bird resting spaces. The façade screen is composed of several vertically post-tensioned ceramic parts that also horizontally interlock. A custom additive and manipulative clay manufacturing process enables the production of zero-waste, variable ceramic parts that have both geometrical and material order. Each part's geometry is first additively manufactured in horizontal contours before a second additive process extrudes clay onto the face of the part to create bird nest-sized spatial pockets. A third method manipulates the clay through smooshing using an incremental metal forming tool to displace the clay, creating various textured material effects. The combined approach provides both spatial and textural variation that reduces large-scale reflectivity within the façade screen, whilst providing spaces for bird resting. The research enables a variable material condition that aims to support a multi-species design approach to the built environment.

In all three projects (along with other projects not mentioned), geometrically varied parts are fabricated through a dynamic formative material process that produced no material waste. Each manufacturing method's specificity also unlocked novel design opportunities, where a specific design character for each project was integral to its manufacturing process. In contrast to traditional design practice where geometrical rationalization is frequently undertaken in later stages of a project to account for manufacturing constraints not embedded within the initial design intent, in the MSD-RAS projects manufacturing methods are baked into design approaches from the outset. Several of the projects also questioned the role of a ceramic façade screen and its possible agency within the built environment.

OBSERVATIONS

The success of a program can be evaluated on many levels. For the purposes of this study, an initial evaluation is narrowed to address the diversity of the student body, the post-study career trajectories they have pursued and the academic contribution of students' work.

Student Body: In the first 3 years, the program supported 46 graduates, averaging 15.5 students/year, comprised of both domestic and international students. With fourth-year enrolled students factored in, the gender balance across the first four years is currently 42% female and 58% male. However, with more than 50% female representation in year four, enrolment is

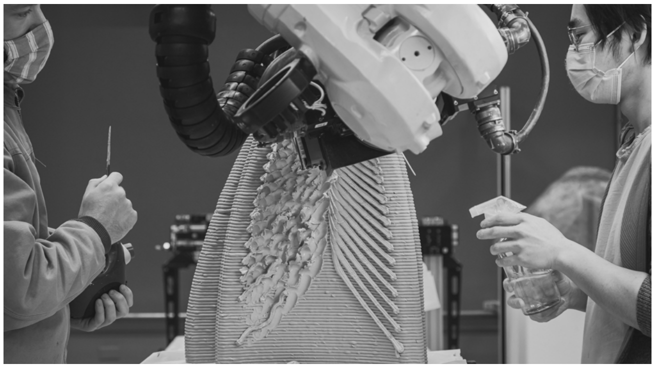

Figure 9 (Top). Robotic smooshing.
Figure 10 (Bottom). Robotic smooshing post glaze fire.
MSD-RAS 2020-1 Spring Semester Project "Robotic Prometheus".

Figure 11. Ceramic multi-part assemblage prototype. MSD-RAS 2020-1 Spring Semester Project "Robotic Prometheus".

trending towards achieving or surpassing gender parity across all years by year five. The first three years' 46 graduates undertook their previous studies at 41 different institutions, demonstrating a broad diversity in the academic background of the student body. While the program caters primarily to architectural graduates from professional degree programs, product designers, mechanical engineers, urban designers and artists made up more than 10% of incoming students. The multi-disciplinary background of students only enhanced team-based collaboration and collective knowledge across the student body.

Career Trajectories: Upon graduation, graduates successfully obtained employment in several different areas such as;

- Specialist architectural practices including Oxman, Jenny Sabin Studio, SOM, KPF, and others alongside custom architecture and art-based companies The Very Many and UAP.
- Industry, such as metal façade fabricator Zahner, stone fabricator Quarra Stone, prefabricated modular construction company Assemble OSM, and others.
- Academic positions as lecturers at RPI and elsewhere, or funded doctorate studies at HKU, SUTD and others.
- Several students were also been hired as full-time staff within Penn's robotics lab for periods of one year or longer, gaining additional hands-on experience after completion of their studies.

The above architectural and industry companies engage in advanced computational design, robotic fabrication or research activities, providing opportunities for graduates to continue to develop knowledge and skills obtained in the RAS program. Academic pursuits were also suitably aligned. The breadth of these employment opportunities and their alignment in subject matter and workflow to RAS coursework demonstrates that the program has already generated a diverse yet coherent set of career trajectories for graduates, that caters to a wide range of interests while providing exciting opportunities to apply RAS taught skills and knowledge.

Further, aligned RAS faculty-led research projects involving design, computation, robotic fabrication and project delivery activities have provided several students with paid employment throughout their studies and as full-time researchers following graduation. RAS graduates have undertaken leading roles in the successful and recently completed Deep Relief Feature Wall in the Middletown Library and Community Center not far from Penn's campus. Led by Weitzman RAS faculty Professor Andrew Saunders, the robot hot-wire cut EPS foam relief wall design was developed through several machine learning and 3D modelling workflows[16]. The project has generated substantial academic coverage and fostered new career opportunities for RAS graduates involved. Another project led by RAS program director Robert Stuart-Smith together with colleague Masoud Akbarzadeh is providing several recent RAS graduates experience on a full-scale robotically fabricated house prototype soon to be constructed on Penn's campus in collaboration with world-leading concrete company Cemex. These projects provide students with built project work experience related to their course of studies, and more time in which to research and acquire their next place of work.

Academic Contribution: In the first year of the program, one out of three student groups sought to publish their thesis project in a peer-review conference and succeeded. In the second year, all four groups wished to publish with three papers accepted. Results on year three peer review submissions are still pending. The publication of four of five submitted group projects across three international conferences demonstrates both students' engagement in the dissemination of their research activities and significant extramural interest in the research-led design activities of the program. RAS graduates also co-authored three additional papers on faculty-led research for both technical research-orientated and discursive conferences[17,18].

Peer-review conference publications suggest that MSD-RAS is contributing to the development of the architectural discipline as opposed to solely training students for a vocation. The diverse yet coherent range of employment trajectories post-graduation also suggests that there is both a market for MSD-RAS graduates and a broad range of industries in which graduates can have an impact throughout their careers, arguably expanding the agency of architecture to operate in domains beyond those supported directly by professional degree studies. It is hoped that the MSD-RAS's contribution to post-professional architectural education provides a critical and creative approach to research-led design that empowers graduates to become future thought leaders, designers and effective producers who positively impact the built environment for decades to come.

PROJECT CREDITS

Figures 1,9,10,11: MSD-RAS 2020-1 Spring Semester Project "Robotic Prometheus". Students: Grey Wartinger, Matthew White, Jiansong Yuan. Instructors: Robert Stuart-Smith, Nathan King, Billie Faircloth, Jeffrey Anderson. TA: Patrick Danahy

Figures 3,4,5: MSD-RAS 2022-3 Spring Semester Project "Dynamic Slip-Casting". Students: Renhu (Franklin) Wu, Shunta Moriuchi, Yinglei (Amber) Chen, Sihan Li. Instructors: Robert Stuart-Smith, Nathan King, Billie Faircloth, Jeffrey Anderson. TAs: Hadi El-Kebbi, Sophia O'Neil, Matthew White

Figures 6,7,8: MSD-RAS 2020-1 Spring Semester Project "Steamed Greens". Students: Yuran Liu, Riley Studebaker, Yuxuan Wang. Instructors: Robert Stuart-Smith, Nathan King, Billie Faircloth, Jeffrey Anderson. TA: Patrick Danahy

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