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Robotic Fabrication in Architecture, Art and Design 2014

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Foreword by Johannes Braumann and Sigrid Brell Cokcan,
Association for Robots in Architecture

with contributions by Aaron Willette

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Foreword by the Association for Robots in Architecture

When the Association for Robots in Architecture was founded in 2010, just a few institutions in the world utilized robots in a "creative" context. While the works of pioneers such as Gramazio and Kohler were already widely published in architecture and design media, only a few selective clusters of creative robotic research existed, but no real network to foster collaboration and the exchange of ideas. Architects and designers considered robots to be machines that are capable of doing great things in the hands of engineers and researchers, rather than tools that can facilitate or even inform their own work in the near future. Thus, the purpose of the Association for Robots in Architecture was clear from the beginning; to "make industrial robots accessible to the creative industry". We pursue that goal with two parallel strategies: On the one hand, by developing the software KUKA|prc for easy robot control within a CAD environment, and on the other hand by acting as a network and platform toward an open access to robotic research.

Following more than a year of preparation, the first conference on robotic fabrication in architecture, art, and design—Rob|Arch 2012—took place in December 2012 in Vienna. Initially conceptualized as a symposium with a few dozen participants, it quickly turned out that there was significant interest from both academia and industry. Eight internationally renowned institutions joined us by offering two-day robot workshops—instead of just talking about the results of robotic fabrication, the robot labs were opened to the public for the very first time, giving participants an insight into the processes and workflows that usually take place in closed research labs. Also the robot industry realized the potential of new, creative robotic applications, with KUKA acting as the main conference supporter, alongside the sponsors ABB, Stäubli, Schunk, Euchner, Zeman, and splineTEX. Finally, more than 250 people attended the conference, with around 100 of them actively participating in the robot workshops.

The effects of Rob|Arch 2012 can still be felt, in the form of collaborations, business deals, and also friendships. Still, within the 18 months that have passed between Rob|Arch 2012 and Rob|Arch 2014, the robotic landscape of the creative industry has grown—and changed—rapidly. Many universities have acquired both small and larger robots, building upon existing plugins for Grasshopper to rapidly introduce their students to programming complex machines. At the same time, an increasing number of artists, architects, and designers are starting to see robotic arms as valuable design tools, while innovative firms in the classic automation business are observing the benefits of new, design-driven strategies for controlling robotic arms. This development is mirrored in the member-list of the Association for Robots in Architecture: While two thirds of the members are universities, the remaining third is made up by individual artists, fablabs, and offices, but also enterprises like Absolut and Boeing. Looking forward to Rob|Arch 2016, this ratio may approach 50/50.

Rob|Arch 2014, and this book, are representative of these changes, spanning the wide range from Google's Bot & Dolly, using robots in cinema, to highly technical robotic applications depending on sensor-based feedback in the contributions from industry partners KUKA, ABB, Stäubli, and Schunk. While in 2012 European institutions hosted universities from the United States, this year the University of Michigan and workshop co-host Carnegie Mellon University collaborate with partner-institutions from Germany, Australia, Spain, and Austria, while Princeton University is teaming up with a university spin-off, Greyshed.

Since the very beginning, the use of robotic arms has been a collaborative effort involving many "trans" disciplines. Rob|Arch 2014 again fosters the exchange of ideas not only between researchers, but also between all kinds of professionals, hackers, artists, and enthusiasts.

We want to thank the editors and conference chairs Wes McGee and Monica Ponce de Leon, as well as their entire team, for their hard work in making Rob|Arch 2014 happen. Furthermore, we want to congratulate all workshop institutions for sharing their ideas and workflows, which is most valuable for the whole community in regards to *open access* and a rapid knowledge transfer. Finally, we are grateful for the generous support of our industry partners, who do not only support the funding of the conference and the workshop infrastructure, but also devoted themselves to supporting young potentials and talents in this new field through the *KUKA Young Potential Award* and the *ABB Mobility Grant*.

We hope to see you all again at Rob|Arch 2016!

Sigrid Brell-Cokcan
Johannes Braumann

Preface

The work presented in this book exhibits the continuing evolution of robotic fabrication in architecture, art, and design. Once the domain of only a handful of institutions, the application of robotic technologies in these disciplines is consistently growing, led by interdisciplinary teams of designers, engineers, and fabricators around the world. Innovators in the creative disciplines are no longer limiting themselves to off-the-shelf technologies, but instead have become active participants in the development of novel production methods and design interfaces. Within this emerging field of creative robotics a growing number of research institutions and professional practices are leveraging robotic technologies to explore radical new approaches to design and making.

Over the last several decades there has been a widely discussed adoption of digitally driven tools by creative disciplines. With designers seeking to push the limits of what is a possible using computational design, parametric modeling techniques, and real-time process feedback, industrial robotic tools have emerged as an ideal development platform. Thanks to advances by established manufacturing industries, the accuracy, flexibility, and reliability of industrial robots has increased dramatically over the last 30 years. The accessibility of the technology to new users has also increased dramatically, with many manufacturers adopting open standards for connectivity and programming. Designers have taken the flexible nature of industrial robotic technology as more than just an enabler of computationally derived formal complexity; instead they have leveraged it as an opportunity to reconsider the entire design-to-production chain.

This is not to say that industrial robots have become mainstream. As with all digital technologies that have entered into creative disciplines, the development of knowledge surrounding the use of robotic fabrication methodologies is ongoing. And while the productive impact of their possibilities and resistances on these disciplines remains an exciting and contested territory, they have had a palpable effect that is actively shaping contemporary discourse.

Rob|Arch

Initiated by the Association for Robots in Architecture as a new conference series focusing on the use of robotic fabrication within a design-driven context, Rob|Arch—Robotic Fabrication in Architecture, Art and Design, provides an opportunity to foster a dialog between leading members of the industrial robotic industry and cutting-edge research institutions in architecture, design, and the arts. In December 2012, the first conference was hosted by its founders Sigrid Brell-Cokcan and Johannes Braumann in Vienna, Austria; now in its second iteration the 2014 conference travels to North America, hosted by the University of Michigan Taubman College of Architecture and Urban Planning. The Taubman College is well known as an academic institution for its diverse and multifaceted approach to design education, as well as its long-standing traditions in pursuing making as a form of knowledge creation.

One of the features of the Rob|Arch conference series is its focus on fabrication workshops, where leading research institutions and creative industry leaders host workshops lead by collaborative teams from around the globe. For the 2014 conference workshops there was an open call for proposals, with eight workshops selected to be held at the University of Michigan, Carnegie Mellon University, and Princeton University. Many of the workshops are based on cutting-edge work currently in progress, and their accompanying texts are published in the "Workshop Papers" section of the book.

The selected workshops cover a wide range of experimental robotic fabrication processes. The contribution from the Institute for Computational Design at University of Stuttgart focuses on their novel methodology for the production of wound composite components using cooperative robotic manipulators to produce variable units from reconfigurable tooling. A collaborative team from the University of Technology, Sydney and the University of Michigan is investigating robotic bending, cooperative assembly, and welding toward the production of complex architectural components. A workshop taught by a collaboration between the University of Michigan and IAAC focuses on sensing and material feedback within a cooperative robotics workcell. Bot & Dolly, one of the Industry Keynotes for 2014, will lead a workshop on procedural fabrication that showcases their innovative control software. Bot & Dolly is design and engineering studio that specializes in automation, robotics, and filmmaking. At Carnegie Mellon University's dFab Lab one workshop will couple cooperative robotic steam bending with integrated sensing techniques, while a team from the University of Innsbruck and the Harvard GSD will lead a workshop utilizing cooperative manipulators for the development of novel building components using phase change polymers. A third workshop at CMU will be led by a team from the Harvard GSD and TU Graz on the sensor-informed fabrication of reformable materials. And last, but not least, Princeton University will host a workshop on augmented materiality, using real-time sensor feedback and custom hardware interfaces to explore the closed-loop fabrication of structurally-optimized components.

Reflecting on the workshop and scientific paper submissions a number of themes emerged that will define both this year's conference and the near-future of robotic fabrication research, many paralleling the state of robotics and automation in other manufacturing industries. Sensor-enabled processes and robotic vision are addressed in a number of papers, both as techniques for in-process tolerance gauging and as adaptive path-planning tools. From the exploration of sensor enabled on site construction techniques, to new techniques for digitally controlled metal forming, designers and architects are expanding the capabilities of the tools at their disposal. Additionally, research projects involving cooperative robots are becoming more common, as research labs around the world have invested in multirobot work cells. This can be viewed as an indication that robotic fabrication research in architecture and design is about much more than just the subtractive or additive techniques analogous to traditional CNC processes: researchers are actively developing production methods which represent entirely new paradigms for fabrication. This is not to suggest that novel work on additive, subtractive, and material forming processes is not occurring; on the contrary, a number of papers address these topics, at scales ranging from the size of a building component, to a mobile platform capable of reaching the scale of a building.

One aspect that has been critical to this adoption has been continued focus by researchers and designers to challenge the norms of standard industrial workflows and machine interfaces. Such research continues to be a key aspect of advancing the possibilities for robotic technology to empower the design process. What is significant, however, is that robotic tools are enabling designers and architects to develop processes that suit the material, scalar, and tectonic needs of their discipline. Robotic technologies provide the ideal platform for developing fabrication processes in an experimental, iterative framework, without reinventing the machines of production.

Perhaps the most exciting trend in the field has been the growing level of knowledge transfer occurring between researchers, designers, and industry partners. The integration of robotic technologies into the workflows of creative industries has demanded renewed levels of cross-disciplinary collaboration. To further this exchange, industry partners were invited to submit papers documenting recent projects in the context of their value to art, architecture, and design. Their submissions illustrate the diversity of research and development going on in the industry, from force-control and adaptive gripper applications demonstrated by Schunk, to lightweight robotic systems by KUKA, dedicated material removal robots by Stäubli, and linked kinematic handling with cooperative robots by ABB.

As new technologies are developed across a wide range of robotic industries, innovators in the creative disciplines will continue to adapt and transform these tools to suit their specific applications. This is more than simple technology transfer, however, as robotic technologies are having a visible impact on the discourse surrounding the means and methods of production in the creative industry. Around the world this discourse is shaping not only how designers look at fabrication technologies, but the entire methodology by which they engage design and material production. As creative industries continue to explore and develop new applications for robotic technology, we look forward to new innovations enabled through collaboration between industry, academia, and the growing community of designers, programmers, and trendsetters surrounding "Robots in Architecture."

The conference chairs would like to thank the CEO of the KUKA Robot Group, Stu Shepherd and Alois Buchstab of KUKA Roboter GmbH who devoted themselves to make this conference and scientific book possible, ABB for their main support of the workshops together with Stäubli and Schunk, as well as our advisory board, and the Association for Robotics in Architecture for the opportunity to organize the conference. In addition we would like to thank the Scientific Committee, composed of architects, engineers, designers, and robotic experts; without their help it would not have been possible to develop the quality of work presented within. Special thanks to our assistant editor, Aaron Willette, for his tireless support. An especially important thanks goes to the entire team at the Taubman College of Architecture and Urban Planning, including both staff and faculty, who have supported the development of the conference. We would also like to thank our peer institutions who graciously agreed to host workshops: Carnegie Mellon University and Princeton University. Finally, special thanks to Springer Engineering for their assistance in editing and publishing these proceedings.

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Part I Scientific Papers

Part I
Scientific Papers

Variable Carving Volume Casting

A Method for Mass-Customized Mold Making

Brandon Clifford, Nazareth Ekmekjian, Patrick Little and Andrew Manto

Abstract The digital era fosters variability and change, though this desire loses traction when applied to methods falsely assumed to be repeatable—casting. This collision has produced a plethora of expensive, wasteful, and time-intensive methods. This chapter presents a method for rapidly carving variable molds to cast unique volumetric elements, without material waste. This method employs a multi-axis robotic arm fitted with a hot-knife to carve foam into mass-customized negatives. In doing so, it re-engages a gothic craft tradition of producing unique volumetric architectural elements. The act of rapidly carving volumetric material mines knowledge from the past in an effort to create novel forms that are not possible in the aggregation of standard building components. This chapter advocates for, prototypes, and analyses this variable, sympathetic, and reciprocal approach that carving once offered the built environment. We found the method to be effective and promising, when informed by limitations and constraints embedded in the process.

Keywords Robotic fabrication · Multi-axis · Formwork · Mass customization · Digital craft · Free-form geometry

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1 Introduction

Architecture has a long history of working with volumetric materials in a variable way. Only recently, as a result of the Industrial Revolution, has the building industry advocated for sheet materials and standardized building components (Clifford 2012). With greater attention paid to robotic fabrication in architecture, there has been a resurgence surrounding the topic of volumetric materials and their capacity to engage computational, algorithmic, free-form, or otherwise complex geometries that are not capable of being described through the Albertian orthographic representations of architectural intent (Carpo 2011).

In recent years, designers have transferred Philibert de L'Orme's method and definition of *art du trait géométrique* (currently known as stereotomy) into the carving of large volumetric positives in expanded polystyrene (EPS) foam (Fallacara 2006; Feringa and Sondergaard 2014; Rippmann and Block 2011). Their projects, though working as an analog for stone construction, argued for the advantages of EPS for its regenerative abilities, lightweight, and machinability (Clifford and McGee 2011). A paper (Stavric and Kaftan 2012) expanded the carving of foam beyond the use of traditional linear cutting geometries into custom profiles. The use of custom profiles is not a new idea either, as it has been used historically for mold profiles in the method of plaster scraping as well as molding shapers for wood moldings and ornamental columns. A project (archolab.com/archives/40) recently applied the use of plaster scraping to robotic processes.

Recently, attention has been paid to the problem of creating complex molds to cast free-form geometries. Many projects have applied subtractive computer numerically controlled (CNC) technology to create custom formwork with high precision. This approach assumes the waste and non-repeatability of the molds in favor of further freedom in geometric creation. Another approach is to approximate subtle curvature through the bending of sheet material against a superstructure (www.designtoproduction.ch/content/view/17/26/). This approach limits the global figure of the geometry to the maximum bending of the material in response to the Gaussian curvature. In a similar method, the use of a variable mold through pneumatics and actuators has been used to articulate a geometry via points across a malleable material in papers such as (Pronk et al. 2009; Raun et al. 2010). Gramazio and Kohler (dfab.arch.ethz.ch/web/e/forschung/164.html) have also demonstrated the advantage of re-usable materials to create serially variable molds. This method is not dissimilar to the use of earthwork as formwork for on-site or tilt-up concrete construction.

This chapter proposes a precise and rapid method for carving negative molds with a custom robotic hot-knife for highly variable free-form geometries without the material waste of typical subtractive machining approaches. It uses the column as an exercise to prototype this method and EPS foam as the carved material.

2 Digital Gothic

This chapter assumes a digital gothic approach as described by Ruskin (1960) in his text '*The Nature of Gothic*'. Ruskin describes the qualities of gothic as being determined by the maker and (his) methods of making. This approach can be conversely opposed to the classic approach of assuming the identical copies of a style that has been pre-determined by one 'thinker'. In establishing this dichotomy, one comprehends the history of division between thinker and maker, as well as the occasional alignment. With the advent of digital technologies in design and fabrication, our profession has found a reciprocal and harmonious relationship between the two. This chapter exercises one development in this reciprocity by generating sympathetic architecture (Carpo 2011; Spuybroek 2011).

3 Fluting and Bundling

The use of fluting or bundling (inversion) has been employed in the creation and subsequent ornamentation of columns for millennia, as demonstrated in Fig. 1. The earliest cataloged column types emerged in Egypt, Assyria, and Minoa 3000 BCE and were made by lashing reeds together at their ends caused them to cinch tightly to one another, and subsequently, bulge outward slightly at their midpoints. Later builders transferred these fluted geometries into stone construction. In his text '*Contrasts*', Pugin (1836) describes the classic period as "white, marbleized ghost of an essentially wooden architecture". Some of the earliest Egyptian stone columns even mimicked the bundled arrangement of reeds through the design of convex flutes. As column orders developed, fluting took on different roles. In the most recognizable column types, Doric, Ionic, and Corinthian, fluting developed by the Greeks as an analog to tool marks left in tree trunks as the bark was stripped away. They had concave, vertical flutes that were carved normal to the stone face. The global form also bulged at their midpoints (a technique known as entasis) referencing the previous reed columns and providing a visual effect that made columns appear more slim and elegant. Gothic builders bundled columns into piers in order to branch ribs above to create vaults. Later builders used fluting increasingly as bundling rhetoric like the twisting Solomonic columns of the baroque period that appear as two columns entwined. While this chapter does not advocate for the simple re-application of fluting as a stylistic choice, it does grapple with these issues due to a method of making constraint (see Sect. 5.1).