Martin Bechthold, Nathan King

Design Robotics

Towards strategic design experiments

Abstract The use of industrial robotics in architecture is characterized by the dominance of two distinct approaches. The first attempts to solve practical problems using engineering methods without affecting design scope. The second is dominated by creative and artistic design experimentation, primarily seeks to inspire, and consciously leaves the practicalities and constraints of the construction industry out of the investigation. "Design Robotics" as a third, more strategic approach links design innovation to the reality of industrial production. The paper articulates its associated research methods and approaches by reviewing recent examples of research conducted by the Design Robotics Group (DRG) at Harvard University. The work, focused on robotically enabled ceramic systems, is a highly systematic form of research that bridges the gap between primarily artistic endeavors and the construction automation research of the building industry.

Keywords: design robotics, automation, ceramics, fabrication, computation

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Introduction

To define when design becomes research and vice versa remains a difficult task. The term "design research" today refers to a variety of approaches that deploy design methods to solve a broad range of research problems (Laurel 2003). These methods, however, are insufficient for work in the area of architectural robotics, a field that began as *construction automation* in the 1980s using methods borrowed from engineering disciplines. Related contemporary academic research has veered toward the other extreme, the production of remarkable, often artistic installations that foreground design. Design Robotics, articulated in this paper, is an alternative approach to "design research" that combines analytic research with open-ended discovery and iterative feedback from material experimentation. This approach is illustrated here using projects on architectural ceramic systems conducted by the Design Robotics Group (DRG) at the Harvard Graduate School of Design.

Established Paradigms for Robotic Technology in Architecture

The short history of robotic technology in architecture is dominated by two opposing trajectories. The first, a pragmatic approach, is focused on resolving the shortcomings of manual labor – inefficiency, low-productivity, unavailability – through on-site construction automation. This effort originated in the massive research and development efforts of many large Japanese construction firms beginning in the 1980s. The second, and currently prevailing approach, is focused on broadening the scope of design by realizing one-off, often highly complex experimental aggregations that seek to understand unique design opportunities for robotically fabricated assemblies.

Construction Automation Approach of the 1980s and 1990s

Beginning in the 1980s several large Japanese construction firms developed automation strategies for the construction of tall buildings. The shared objective was to reduce the demand for construction workers, increase productivity, and improve site safety (Tanijiri 1997). By offering comfortable, almost factory-like, working conditions the industry hoped to attract young workers who could find less physically demanding and well-compensated jobs in other industries. Comprehensive construction automation systems were developed by Fujita Corp., Obayashi Corp., Kajima Corp., Shimizu Corp., Taisei Corp., Takenaka Corp., as well as by others. Different systems were conceived for pre-cast concrete and for steel construction, some "extruded" the building using an automated assembly floor at the top (Obayashi ABCS) or near the top (Fujita Corp.), others developed "push-up" systems that assembled all pre-configured modular components on the ground floor by incrementally jacking up the growing buildings with one complete floor at a time.

These systems, despite their unquestionable sophistication, depended on standardization of construction. Obayashi's ABCS system, for example, was initially designed to support the construction of high-rise buildings with rectangular plans and cores at opposite ends, and the first 5 applications over 10 years were limited to this building type. Only the last use of ABCS expanded the system's capability to a square plan with a central core (Ikeda and Harada 2006). Floor-to floor variations, typical for many contemporary high-rise designs, would have created inefficiencies or, if vertical material transport systems were affected, would be impossible to accommodate.

The initial R & D costs for each system were significant. Site productivity increased slightly compared to conventional construction, but the added value of these comprehensive automation systems was ultimately small. When the Japanese construction boom collapsed in response to the national recession, all automated construction systems were retired. Personal interviews by M. Bechthold in Japan in 2007 showed that none of the large corporations intended to reuse their automated construction technology. Along with economic conditions architectural preferences had changed, with demand for standardized buildings diminishing. Japan's automated construction systems were unable to effectively support the construction of non-standard, contemporary architecture.

Construction automation approaches today have shifted towards supporting pre-fabricated building systems (e.g. brick, steel, concrete), and industrial automation drives the high-volume production of ubiquitous building products such as ceramic tiles. Both approaches are geared towards improving productivity and replacing human labor with robots, as stated by Andres (1994) and Pritschow (1995) in their work on robotic bricklaying systems. Design-driven work on robotically placed non-standard brick patterns, by comparison, is a more recent phenomenon (Bonwetsch 2007) that continues to thrive in the academy today.

Robotically Enabled Artifacts and Installations

The introduction of industrial robots in academic laboratories triggered a wave of creative and complex installations that intellectually continued the experimental design work conducted with numerically controlled machine tools and routers in the early 2000s. Beginning with the ETH Zurich work cell (2005) and Harvard's robotic environment (2007), the popularity of industrial robots as more capable devices for experimental architectural fabrication continues to spread. Today's pursuit of industrial robotics at schools of architecture has clearly raised the cutting edge of digital fabrication to a new level. Throughout Europe and the United States robotic experimentation is geared towards furthering the understanding of new opportunities that robotic fabrication may bring to component, building, and product design. The current situation is largely driven by the academy, while fabricators, for the time being, remain spectators and are only beginning to invest in robotic fabrication technology. The situation, thus, is markedly different from the 1980s construction automation approach.

A common strategy employed in this type of robot-related work leads to the development of a project through a "bottom-up" approach that takes specific robotic process opportunities, including the ability to individualize or efficiently handle large numbers of units, as a starting point. This "discovery" phase remains intentionally loosely defined and open ended – an informed "play" that combines both digital and material experimentation. A second step is to systematize and rationalize, to some degree, the most appropriate experiment and to design a prototype that best illustrates the most novel design discoveries. In the third, and final step this piece is executed and evaluated.

Custom-automated code generation strategies have emerged, are now widely used, and have led to the creation of plug-ins and software components that automate robotic tooling within the digital design environment. DRG's automation tools link geometry data from a number of software platforms (e.g. Rhinocerous, DigitalProject, Catia, etc) to the robot control interface by bypassing proprietary manual robot programming and enabling the simplification and translation of many highly individualized model-driven movements with ease. The usually striking end results are often inspirational, but are difficult to connect to the reality of architectural production. The authors thus propose a strategic design research approach.

Design Robotics: A Strategic Research Method

A rigorous analysis of the chosen building or material system is the first step in more strategic research on architectural robotics. This analysis, while including obvious technical aspects relating to fabrication, must be broad enough to understand all relevant aspects of the given system, including production, distribution, economics, and end-use. This step is crucial when defining the problem or opportunity to be addressed such that new solutions can emerge. Deeper knowledge is acquired as the work proceeds, often allowing the definition of the research problem to be incrementally improved. Evaluative frameworks emerge incrementally and guide the research. The design of an experimental installation frequently serves as a proof of concept. Its features are strategically chosen such that its design to production yields generalizable knowledge that addresses the research problem within its broader industry context. Design Robotics thus represents a hybrid research method that combines bottom-up, technology driven design inquiry with traditional, problem-centered approaches. DRG is not the only group pursuing this type of research. Research on non-standard assembly of brick, wood slats or other materials can follow similar principles (Gramazio Kohler 2008). But DRG's approach has pursued the customization of the basic module itself as its core interest, thus potentially supplementing and enhancing robotic assembly procedures. Expanding the scope of robotic intervention forces the analysis of existing processes to penetrate deep beyond assembly procedures and embrace far broader industrial production issues. The following illustrates DRG's approach through a discussion of ongoing research projects on architectural ceramics.

Ceramic Industry: Contemporary Mass-Production

The DRG has been in collaboration with an industry association of Spanish tile producers (ASCER Tile of Spain) since 2009. The initial phase of research included a comprehensive analysis of the industry in terms of products, production processes, and research and development infrastructure. Spanish tile producers emphasize superior quality and innovative surface finishes as they compete with many other international brands. The industry primarily uses large hydraulic presses and steel molds to form flat tiles from dry clay bodies. Only a few companies form clay by extrusion through shaped steel dies. After the initial forming process tiles are post-processed on highly automated computer-controlled production lines designed to treat surfaces and edges. Surface finishing equipment includes numerically controlled ink-jet technology that prints patterns and images on pressed tiles. Computer-controlled techniques are widely used for packaging, storage, and logistics. Most companies sell their tiles through distributors; only one company has built a strong brand and a related distribution network. Tile production is based on demand predictions, and tiles that cannot be sold produce storage costs, and are eventually sold at discount prices abroad.

Several problems became clear. First, high-volume production techniques based on predicted market demands make customization of tiles – beyond what digital printing technologies could deliver – virtually impossible. Only one facility was able to produce customized, three-dimensionally formed ceramic elements for an ambitious architectural project. Considering current architectural trends towards complex form and individualized construction the need for custom building products is bound to increase. Growing demands on operational building performance may also reinforce that trend (Bechthold 2011). Product customization and responsiveness to more individualized market needs appeared to be a challenge for the industry, and thus was identified as the primary research agenda for DRG.

A second problem became evident while comparing automated tile production lines with downstream manual tile installation processes. Standard manual tile installation is archaic – slow, costly, and prone to error (King 2012). Interviews with tile producers revealed disconnects between the production industry and tile installers, even though installation is a significant cost factor of finished tile surfaces. It became clear that a potential for innovation might exist when considering tiles as a material system from production to installation, instead of merely looking at manufacturing aspects. Further research

Figure 1 Automated Spanish tile production facilities

showed that cutting waste and the amount of spare tiles purchased for future replacements exacerbate the cost disadvantage of tile finishes compared to other surface finishes. Cutting waste also presents an environmental burden. For the 2010 U.S. tile consumption of 23.2 million square meters the embodied energy of an assumed 5% cutting scrap is equivalent to a staggering 13.6 million liters of regular gasoline.

Technological innovation always requires investment. To understand potential opportunities for robotics in the production and installation of ceramic systems several cost analysis were conducted. First the cost impact of manufacturing equipment on the cost of a tile (as sold from the factory to the distributor) had to be determined. Data for Spanish production was unavailable, so published information from the Italian tile industry (with a similar product and process structures) was analyzed (Fiori 2007). The research showed that on average only 7% of the manufacturing cost of a pressed tile is spent on equipment amortization, a small yet not uncharacteristic amount for high-volume producers.

Next, the ratio of installation costs to material costs was analyzed. The typical US installation cost starts at 270 $/h for a square meter of mosaic tiles, which easily outweighs the cost of tile and grout. Prices for placing non-standard patterns (e.g. custom mosaics) are far beyond average construction budgets (King 2012). The cost analysis of manufacturing and installation assures that robotic interventions are fundamentally realistic from a cost standpoint.

Is the Spanish ceramic industry technologically ready for robotic systems? Factory visits showed that many Spanish producers already use 6-axis robotic manipulators for packaging. These companies possess the technical know-how needed to operate robotic work cells and in addition to proving viability based on cost, the initial research also concluded that robotic interventions are realistic from skill-level perspective. The potential customization of ceramic products offered through robotic intervention allows greater product differentiation that responds to dynamic architectural needs. New ceramic systems must also address existing problems of waste and inefficient installation procedures.

Material Systems: Ideation Stage

How can *design research* "invigorate" a material system as old and well established as ceramics? The broad research agenda outlined above leaves many different pathways open. To gather a number of ideas several experimental studies were conducted both by the research team and by students in as-

Figure 2 Financial breakdown of the ceramic industry showing only 7% amortization costs

sociated courses. These open ended, almost playful, studies used hands-on, computational and robotic explorations that were guided by the broadly framed agenda of "customizing ceramics" and "waste reduction". A bottom up approach largely characterizes this phase, albeit guided by the general theme of customization and waste reduction as defined at the outset. The bottom-up approach takes inspiration from the material system itself. Within the material system we refer to the following:

- General physical and aesthetic material properties: for ceramics this covers the properties of various clay bodies and their admixtures, such as moisture content, colors, dry-time, mechanical strength in green and fired state, porosity, as well as many other factors.
- Ability of the material to be shaped and formed: clay as a plastic material can be freely formed through processes such as slip casting, extrusion, and molding. Industrial methods work mostly with pressed tiles that can accommodate a minor degree of three-dimensional shaping. Extruded forms are linear and have a range of flat to complex profiles. To enable customization new processes must address these limitations.
- Opportunities and limitations of 6-axis robotic manipulator: Repeatability and precision can be a factor to be considered for the material system, but in the case of clay the material shrinkage is usually larger than process-inherent tolerances. Tooling for the robot is another question – in order to reduce process complexity it is often desirable to limit tool changes where possible.
- Characteristics of related industrial production processes: in the case of clay all production equipment is geared towards linear movement of ceramic pieces along conveyer belts and rollers, from initial forming to surface finishing, drying, firing, and dimensional rectification, Integration into industrial processes means at least one flat surface of the ceramic piece has to exist such that parts can rest on standard conveyer belts.

Many early ideas were discussed with industry experts. Clay extrusion was identified as the manufacturing process with the largest potential for part customization. The steel dies used in extruding linear clays forms are relatively costly, thus prohibiting small productions runs for custom parts. Several experiments explored robotic intervention geared towards supporting individualized production methods. The first design experiment developed a variable extrusion die that could change shape during extrusion. An industrial version would include numerically-controlled drive motors that alter the die geometry, thus enabling continuous product variation while maintaining a constant wall thickness.

Another extrusion-based experiment addressed customization through variable robotic cutting after the initial shaping process. During industrial processing the linear extrusion is cut to length or into its final shape using a variety of cutting mechanisms including wires and blades. Extruded hexagonal tiles, for example, are cut from flat slabs using hexagonal blades. The first attempt to adapt this cutting process and enhance its versatility through robotic intervention involved a fixed blade assembly that was manipulated to generate a family of façade components. A third customization project proposed a robotic wire-cutting process that shapes 5 sides of an extruded block into ruled surfaces with varying degrees of complexity. The envisioned industrial scenario was simulated by equipping a 6-axis industrial robotic work cell with a custom wire-cutting end effector designed for use with clay materials (Andreani 2012). Customization opportunities for pressed tiles exist primarily in the installation phase. Initial experiments and detailed precedent research confirmed the potential to rapidly and precisely place tiles using an industrial robotic work cell. Several experiments were conducted that involved the placement of dimensionally modular tiles at a digitally defined position using a pneumatic suction gripper. (King 2012) The system can also accommodate tiles of varying shapes and formats. In addition to developing technologies for robotic tile placement the entire tile installation workflow was reconsidered. Instead of installing robots on site, panels are robotically tiled off-site. Tile panels are then transported to site where they are installed. (King 2012)

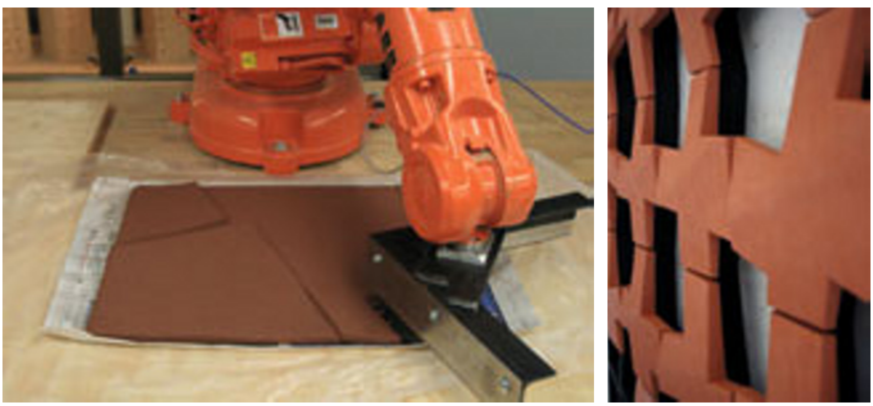

Figure 3 Post-extrusion robotic cutting and resulting prototypical facade assembly (students: Mauricio Loyola and Jeremy Keagy)

Figure 4 Prototypes produced during flowing matter research using a custom end effector (students: Stefano Andreani, Jose Luis Garcia del Castillo y Lopez, and Aurgho Jyoti)

From Ideas to Concepts: Evaluation and Development

During initial ideation, experimental "sketches" are evaluated and refined in pursuit of the larger research objective. Refined "sketches" are used to guide the ongoing creative experimentation, but without over-constraining it. Two research projects will illustrate the approach, first, the robotic extrusion of individualized ceramic façade elements, and second, the automated placement of non-standard tile patterns based on digital images or other algorithms.

Building on initial research into the possibility of variable extrusion a prototypical façade system was envisioned that enabled the creation of high-performance, custom components that can respond to specific environmental or aesthetic parameters. By strategically identifying the ceramic façade as a research platform several research trajectories emerged that led to the production of an Integrated Environmental Design to Robotic Fabrication Workflow (Bechthold 2011). Here a custom workflow linked a digital design model through several Grasshopper-based optimization modules that accounted for environmental performance optimization, material properties (shrinkage and deformation), design for robotic fabrication, machine code generation, and building integration. Parallel to the digital workflow was the development of a novel manufacturing process that utilizes a robotically actuated pin-mold and novel extrusion-based robotic material deposition system designed to create accurate individual façade elements and building components.

Figure 5 Image-based pattern generation and automated robotic tile placement processes

To evaluate the potential for customization using robotic tile placement a second workflow was established that incorporates both image-based and pattern-based algorithms into a design model that can be used to automate the programming of robotic movement during tile placement. (King 2012) A novel modular production strategy was proposed that enables the factory-based placement of tiles on modules that would be transported and installed onsite. This project combines the value of non-regular, non-standard tile patterns with a reduction in overall labor costs and shorter onsite installation time.

Typical evaluation criteria for DRG's ceramic research projects beyond purely technical questions include the following:

1. What kind of customization can be achieved with the process? Robotically manipulated extrusion processes typically result in geometry variations, while robotic tile placement can generate non-standard tile patterns.
2. What value does customization add to the material system and its applications? Robotic extrusions can achieve greater formal freedom for shading lamella and other elements while maintaining excellent building performance. Robotic tile placement produces non-standard tile patterns that are not economically possible with manual placement techniques.
3. Can waste be reduced? Both robotic extrusion and robotic tile installation are on-demand processes that can potentially reduce waste. The pattern generator can be configured such that tiles do not need to be cut – dimensional differences can be accommodated with varying grout line width.
4. How are installation procedures affected by part variation? Façade elements would normally be installed using custom connectors. Robotic tile placement requires a new approach of semi-prefabricated sheets, factory made, with on-site installation reduced to mounting pre-tiled sheets on prepared wall surfaces.
5. To what degree can the process be incorporated into state-of the art industrial production lines? Modular concepts are crucial when considering industrial integration. Robotic extrusions, for example, could be a stand-alone concept, but the configurable molds could easily be used for slumping flat extruded clay slabs. Robotic tile placement leaves current production methods for pressed tiles unchanged, but requires new business models for installers that move much of their activities to the factory floor.
6. How could parts be packaged and shipped? Flat tiles for robotic placement are shipped on pre-tiled sheets that can be efficiently stacked. Shipping costs for custom robotically extruded façade elements can be reduced through nesting algorithms already implemented to optimize kiln use.
7. Is there need for a new distribution model associated with the proposed processes? Robotic extrusions could easily integrate into existing supply chains of producers, installers, and façade companies. Robotic tile placement requires more direct links to be forged between the end-user or designer (whoever configures the pattern) and tile installers. Online pattern configuration would most readily provide this connection.

Work in this phase iteratively develops and test ideas for technical feasibility, design interest, and industrial integration, thus systematizing and rationalizing the initial experimentation.

Process Prototypes: Proof of Concept

The proof-of-concept involves the production of a prototype large enough to provide credible evidence of research agenda, and also allow for critical evaluation. Full production of large prototypes is unlikely to yield new insights in the academic setting because the work is geared towards the industrial or professional fabrication context, not towards the making of an artistic artifact. During the research described, several types of prototypes were developed to test ideas and provide iterative feed back during process development. These prototypes are critical to the work but are often specific to certain aspects of the research agenda, dry-placed tiles to tune accuracy or flat robotically extruded shapes to test material properties, for example. The proof of concept prototype is strategically defined to resolve certain speculative aspects of a proposed system as well as reconcile in-depth analysis of a given material system, novel process development, and design potential. In some cases the proof-of-concept prototype represents a piece of a larger system or an entire system in itself. During prototyping the robotic arm may be used to emulate a proposed process such as production line integrated wire cutting, or, in the case of robotic-tile placement and robotic extrusion, represent an actual proposed production process.

During the development of the previously described robotic extrusion process a design experiment was chosen that tested the workflow using an extreme scenario requiring shading and controlled views on the east, south, and west sides of a semi-circular glazed atrium space. The entire facade was used to calibrate the digital workflow but only a representative section of the shading system was ultimately fabricated. This section contained enough complexity and variation to both illustrate technical solutions and design potential of the novel manufacturing process (Bechthold 2011). In the case of robotic tile placement the entire workflow was demonstrated during the production of a single modular image-based mosaic (King 2012) This prototype used a custom pattern generation algorithm to reproduce a recognizable image using a series of modular tiles (see Fig. 6). The resulting digital image was used to generate robot code that in turn enabled robotic tile placement. In addition to presenting the technical feasibility of robotic placement the physical prototype also validated the proposed modular installation strategy.

Figure 6 Prototypical manufacturing strategy including robotically actuated variable pin mold, robotic extrusion process, and finished proof-of-concept prototype

Conclusions

The use of robotics in the academy is entering a strategic mode of operation that differs markedly from both the traditional industrial automation approach to solving problems and from the digital crafting of one-off installations. DRG studies both part customization as well as the robotic assembly of modules. Research activities are grounded in the analysis of the construction or industrial context – learning to ask unconventional questions here yields research opportunities that otherwise remain opaque. The analysis yields a general research direction that guides the following, open-ended experimentation phase. Here physical and digital experiments produce many ideas in rapid sequence. Rough prototypes, even those produced manually, provide early feedback on opportunities, but also help failures to emerge quickly. The evaluation criteria derived through the analysis are used to filter out ideas for further development, and prototyping is used iteratively to answer questions that gain specificity as the research proceeds. The work, while focused on bringing design to bear as a value on ceramic material systems, is embedded in the industrial context, but not dominated by it.

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