



Interlocking Units for Robotically Fabricated Architectural Structures

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Abstract. Throughout this paper, we introduce a novel design-driven method for the robotic assembly of unit-based structures. The goal of this research is to establish a method to robotically fabricate discrete structures, using pick-and-place robotic manipulation and customized 3D-printed geometric units. Thus, the methodology allows for the bespoke discretization of architectural solid models into interlocking architectural units. Investigating how design can reduce error in the robotic fabrication process, a significant feature of this research is the application of mechanical coupling for the creation of self-interlocking geometry. This method is able to correct errors in robotic manipulation for the precise robotic fabrication of architectural structures. Reducing errors in the assembly process through the design of geometric units expands the field of architectural robotics to designers. Through a series of assembled architectures, fabricated through both additive and subtractive manufacturing techniques, the research explores the idea of an automated system producing unit-based structures using pick-in-place robotics and digitally fabricated units.

Keywords: Pick-and-place · Robotic fabrication · Interlocking units · Brick stacking

1 Automated Assembly for Architecture and Construction

Automation for assembly is now a common method of early-stage assembly in automotive and engineering practices. In contrast, building construction has struggled to include new technologies, such as robotics, and still relies primarily on manual labor to manufacture buildings. This is particularly the case for small buildings such as houses in North America composed of thousands of small timber or brick elements. The small-scale building industry is ready for new computer-based technologies that can automate or assist workers as part of building production. This paper presents the idea of a robotically assisted assembly of non-standard interlocking blocks. We believe this method to be supportive of the constant search for rapid production of small non-standard structures.

1.1 The Current State of Construction

Rapid assembly of unit-based structures is as old as the field of architecture. Traditional forms of manual construction use standardized sets of materials for architectural design

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and building. These construction and manufacturing systems rely on the precision of tradesmen, craftsmen, and laborers to design custom structures. For example, brick construction relies on standard masonry units and mortar to build both complex and simple structures requiring hundreds of hours of manual instruction and labor, for simple tasks such as block stacking and mortar setting [16]. Low-cost, high-skilled labor for modern construction is in short supply. It is clear that assistance of some type of automated system is needed for the design and building industries.

1.2 Automated Brick Assembly

Studies in automating architectural fabrication processes led to the development of robotic fabrication techniques including robotic bricklaying [22], robotic timber assembly [9] and robotic printing [7, 10]. Despite robotic bricklaying and stacking sitting at the forefront of robotic construction research, there is a need for an additional inquiry into these approaches to expand the field. Since the beginning of robotic brick construction research, methods of robotic brick assembly have attempted to automate architectural construction with standard bricks and blocks [3]. These methods include block assemblies of uniform and non-uniform walls with standard masonry units typically found on construction sites [4]. This is challenging research due to the necessity of high precision and accuracy in the robotic fabrication process, which is typically inaccessible to designers, architects, and contractors. Examples of robotic dry-stacked brick assembly demonstrate these challenges in robotic fabrication. As one of the earliest adopters of robotic architectural assembly, Gramazio Kohler's work around challenges in precision by fusing robotic pick and place operations with computational vision systems [5]. In the case of brick stacking, robotic fabrication research, which attempts to reproduce the infinite patterns and possibilities of design, is limited by the constraints of the robotic arm.

To work around problems in brick stacking with standard architectural units, architectural roboticists can find inspiration outside of using computer vision systems for robotic brick stacking in non-standard interlocking architectural units. For example, research in interlocking brick assembly, fabricated with a multiblock press using common soil, presents a low-cost, mortarless method of wall construction. In this case, interlocking blocks are assembled by hand [11]. Additionally, a system of interlocking blocks cast of concrete from digitally fabricated rubber molds has been presented as a mortarless solution to patterned, customized buildings. Also, presented is a generative system of block-making that yields location-specific, interlocking blocks ready for mortarless assembly [12].

The present work describes the idea of an automated system of unit-based wall production using pick-in-place robotics and digitally fabricated units. These systems present new opportunities for endless variations that can produce unit-based wall assemblies. With the introduction of robots into the construction site in the late 20th century, automation has discovered difficulties in automated solutions to masonry construction in bricklaying. Currently, there is an opportunity to rethink existing solutions and discover improved techniques.

1.3 Robotic Construction

The concept of on-site brick-laying robots expanded in the 1980s and 1990s with solutions like ROCCO, ESPRIT, and BRONCO [1, 6, 15]. They relied on standardized parts, rigid planning, controlled environments, and heavy-duty equipment to execute assembly tasks. In the 21st century, dry-stacked robotic bricklaying solutions by Gramazio Kohler explored new approaches to automated brick construction of complex structures, while tech companies, like the Semi-Automated Mason [3] and Hadrian X [8] worked toward fabricating conventional structures. Though many automated approaches to robotic bricklaying exist, there is insufficient use by designers of complex geometry, and automation to design and generate structures. Looking toward the future of construction, novel architectural unit designs can assist the complex tasks of automated construction.

1.4 Design Unitization for Architectural Construction

Recently, digital fabrication has expanded the field of architectural design to produce complex geometries at scale using machine-driven additive and subtractive manufacturing processes. For the office of Frank Gehry, the process of tessellation, discretization, and fabrication of large-scale curvilinear structures is seen in works like the BMW pavilion, the Guggenheim Museum in Bilbao, and Zullhoff Towers [13]. These projects use standardized materials and machines to create custom discrete units of architectural assembly. More recently, research projects investigating non-standard materials and their fabrication have seen a continued effort to merge bespoke found materials with digital fabrication procedures to create expressive architectural designs [14]. Though these methods make use of digitally processed designs and digital fabrication procedures, they require fabricators to assemble these structures by hand, continuing a legacy of manual assembly in construction. In the future of robotic construction, designers can leverage the capacities of additive and subtractive methods of fabrication to fine-tune robotic assembly for designers.

1.5 An Opportunity for Design

As it stands, robotic manipulators afford levels of speed, flexibility, and function through customization, automation, and precision in the design world. Yet their lack of utilization can be attributed to the need for simpler procedures that leverage the strengths of digital design and digital fabrication. If digital fabrication methods can rapidly produce custom architectural modules and robotics manipulators can repeat stacking operations, how might researchers combine these strengths for architectural designers? This paper argues that bespoke interlocking construction units can achieve precision geometry without precise movements. For precision machines, such as robotic arms, which need perfect conditions to operate, customized geometry can afford interplay between design intent and material reality. Developing design features to correct for imprecision in the environment, machines, and structures without computational vision systems is key for extending precision construction outside the context of the perfect conditions of a warehouse.

2 Methods

To develop a modular system of interlocking assembly units, an automated process was used to construct architectural blocks from 3D-printed materials. The research in this paper uses a low-grade PLA and a Sindoh 3D-Wox-1 desktop FDM 3D-Printers. To generate the g-code for the 3D-Printing process, the methods employed the Sindoh STL slicer. The units were modeled using Rhinoceros 7 and the robotic path planning was conducted in Grasshopper using KUKA PRC [2]. The robotic manipulator used for the automated assembly was the Kuka Agilus KR6 R900 with a RAD two-finger parallel gripper as the end-effector. With these tools, the research created designs and generated wall assemblies of interlocking units.

From a rectangular wall profile, 2D profiles are generated and projected onto the surface of the 3D CAD model wall to create outlines for the interlocking tessellation shapes. Wall design thickness was tested at the model scale to fit within the constraints of the robotic manipulator and subsequent end-effector. The 2D shape information is developed from a v-groove grammar developed in the paper. The 2D shape information determines the size and shape of geometric design features for the physical design production of the custom architectural units. From the tessellation, three combinations of shapes are created to start, continue, and stop the layer-based assembly procedures. The decomposition of the 3D objects into 2D shape profiles leveraged an adapted version of the materialization processes as described by Sass and Oxman; although, the research process outlined for model unitization is akin to the fabrication procedures seen in the Sass and Knight paper outlining physical grammar production [17, 18].

2.1 Producing 3D-Printed Units

Design iterations were conducted to produce interlocking 3D-Printed units. The major constraint examined in the study was the implementation of v-grooves on unitized structures for their interlocking capabilities. Digital fabrication, through additive manufacturing, provided a flexible method of automated construction to create customized modules for their interlocking capabilities. The process allowed for the transformation of 2D and 3D design data to the physical environment using desktop 3D-Printers by streamlining the processes found in conventional modular construction procedures. In particular, eliminating processes of formwork and brick presses reduced the fabrication steps, while maintaining geometric accuracy.

2.2 Design Unitization

The design of individual interlocking units uses a top-down approach to discretize designed geometry into individual parts for 3D-Printing. Starting with an initial structure, designs are subdivided into labeled shapes. Using the shape grammar formalism, each labeled shape has a distinct set of attachment features applied to it that creates the interlocking geometry [18, 20, 21]. On shapes labeled *A*, subtractive v-grooves are added to the interior of the structure. On shapes labeled *C*, protruding v-features are added to the object's shape. The features on shapes labeled *A* and shapes labeled *C* form a set shape from the initial wall design before the application of the discretization process and

shape rules. Shape *B* is created by applying shape addition, which merges overlapping elements of shapes *A* and shapes *B*. By adding shapes, *A*, *B*, and *C* together the elements for the original wall structure can extend the length of the initial wall design. From these shapes, designers can use digital fabrication to create interlocking geometric units and robotic fabrication to assemble structures (Fig. 1).

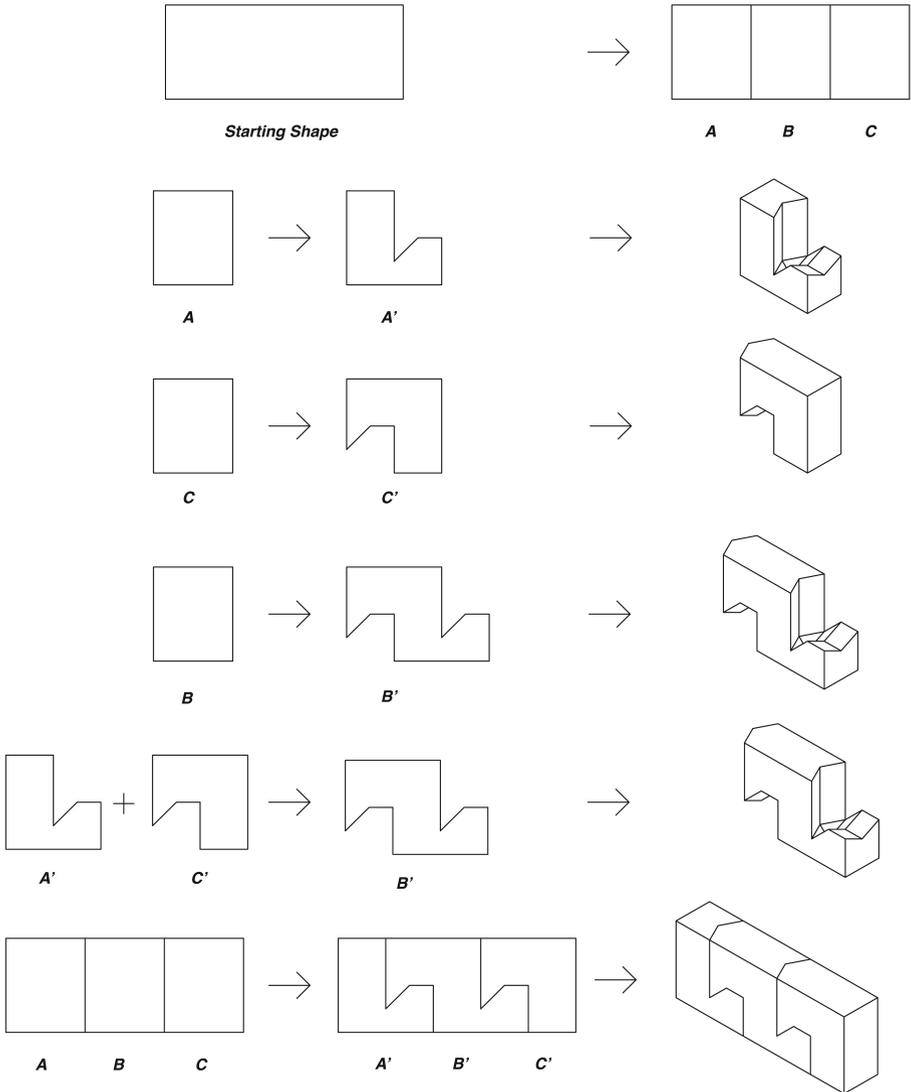


Fig. 1. The unitization of interlocking geometries using the shape grammar formalism

2.3 Robotic Assembly

The robotic assembly of individual units is constructed in a sequential manner starting with shapes labeled A' and ending with shapes labeled C' . Because individual units were created in the Rhinoceros' CAD environment, their digital assembly information, which contains the shape rules and subsequent assembly, is easily transferred into Grasshopper's Kuka PRC workflow. In the grasshopper environment, discrete poses of the construction units are located and mapped, from the centroid of each object to the localizing frame for the final positions in the constructed wall. Using the frames of the object, the system relies on the path-planning and trajectory optimization of the Kuka PRC plug-in to use pick-and-place manipulation to position construction units in place. Because of their interlocking capacity, once a localization frame has been established by the units for robotic assembly. Using A' shapes, the pick location of shapes A' and C' are referenced by positioning shape B' or C' in shape labeled A' . With the correct frame referenced in the digital environment, the method follows the robotic task-planning assembly logic of

$$(A' + (B') + C') \quad (1)$$

where B' can be added indefinitely to assemble the final wall structure (Fig. 2).

2.4 Masonry Production of Assembly Units

To challenge the methodology, portions of this research investigated alternative modes of fabricating custom architectural units for assembly. Rather than 3D-Printing units, to function at scales starting at the desktop and extending beyond, the research looked at concrete casting units using custom formwork for large-scale industrial robotic assembly. The concrete fabrication method employed the following: 1" thick Polystyrene Foam Sheets, Quickrete Concrete mix, and an Onsrud CNC router. The two foam sheets are glued to create stock for the mold. Due to the complex nature of the geometry, the mold was created in two parts, having to be flip milled for each unit to create both parts of the mold with the intended geometry. After 3D CAD designs are generated from the interlocking shape rules, Boolean Subtraction is used to create a negative form within the stock, and from the resulting geometry, G-Code is created for the CNC machine to mill the mold. Using the two-part mold, the concrete mixture is cast and removed to create masonry versions of the interlocking units (Figs. 3 and 4).

3 Results

From these studies, the research finds that the role of interlocking architectural units can assist processes in robotic fabrication and assembly. Through the application of the shape grammar formalism, architectural forms are unitized for construction in the physical and digital environments. Using the digital workflow provided, designs generated in CAD translate to visual programming, through specialized plugins for design implementation, robotic path-planning, and robotic control. In the end, the digital-to-physical workflow codified the assembly and fabrication sequence (Fig. 5). Furthermore, through the implementation of 3D printing, architectural designers can easily fabricate

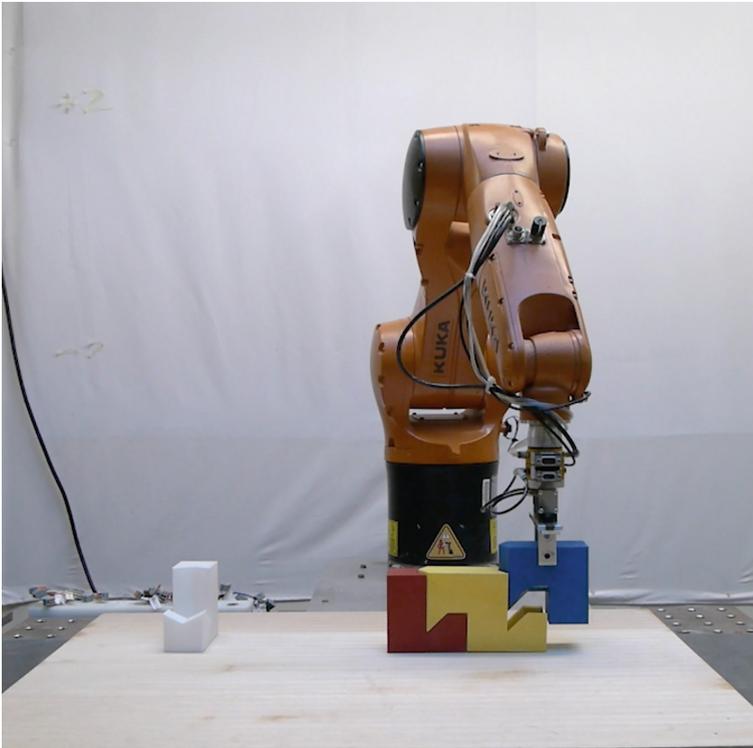


Fig. 2. The robotic construction of 3D-Printed interlocking units. Where unit shape C' is added to unit shape B'

customized geometric units for interlocking assemblies. Due to the translation of shape rules into the digital environment, multiple methods of digital fabrication can be used to generate interlocking units, such as subtractive manufacturing through CNC milling. With physical and digital intelligence working together, designers can scale their unitized structure using different materials and forms.

3.1 Error Correction and Interlocking

Unlike traditional methods of construction that rely on geometrically simple architectural units, this research introduces geometrically complex unitized modules for self-interlocking structures. When assembled in the correct sequence, the geometric faces of the architectural modules allow for the registration of the architectural blocks to work with gravity to interlock and slide into place. The registration of architectural blocks into self-interlocking structures reinforces previous research in kinematic coupling and exact constraint design [19]. These research topics explore the role of contact points in precision mechanical assemblies. By aligning the design shapes rules to generate contact points through integral components of architectural modules, which constrain three degrees of freedom, we developed interlocking units for assembly. We found that there



Fig. 3. Design of interlocking concrete assembly using custom units *A' B' C* where units form components of a wall structure



Fig. 4. Design of interlocking concrete assembly using custom units *A' B' C* where units form components of a wall structure

must be a minimum of two contact points during the assembly sequence for units to interlock into the desired shape of a wall.

Since the architectural blocks contain precision geometry, that uses registration points and gravity to interlock, they eliminate imperfections in the robotic assembly processes. Nevertheless, this assembly process is reliant on low coefficients of frictional forces to enable the sliding and interlocking effects. For 3D printing, variables in printed layer heights, infill, and surface finish play key roles in the block's interlocking capabilities. In our concrete fabrication tests, we found that variables in mold surface finishes, material mixtures, and finishing processes play important roles in curating the frictional forces of masonry blocks. With controlled frictional forces, the research shows that interlocking geometries can work around imprecision in end-effector position-controlled robotic manipulators completing architectural assembly tasks. Simple robotic assembly procedures, in addition to those using computer vision sensors and tools, require high levels of precision to determine positions for assembly sequences [4]. With the methods illustrated in the paper, designers can create precision geometric units that create variable structures and designs. In other words, instead of working toward strict positioning in robotic manipulation, designers can create designs that account for inexact manipulation in the layer-based assembly process.

3.2 Digital Fabrication for Bespoke Object Generation

Incorporating methods of additive and subtractive fabrication for custom architectural fabrication aided the robotic fabrication process. Due to the highly complex nature of architectural units in the research, custom fabrication methods relied on precision machines for geometric accuracy. In the 3D-printing process, the additive method of FDM printing allowed for a streamlined method of fabricating architectural units taking the digital design information from the computer directly to the machine to create objects. Conversely, the method of subtractive manufacturing through CNC machining required the most of steps in the fabrication process. After the digital CAD design of the interlocking units, the method required stock preparation, CNC machining, mold assembly, and masonry curing for the assembly to be completed. Furthermore, the accuracy of the masonry units depended on the precision of the mold, the quality of mold assembly, and the material efficacy of the concrete mixture. Though there is a tradeoff in material size, strength, and precision, 3D printing as the first test proved successful at validating the research goal of creating interlocking assembly modules for robotic fabrication.

4 Implications

The next steps of this research seek to validate existing claims by robotically fabricating complex architectural forms, enclosures, and structures. Methods seeking to leverage layer-based assembly, while reducing the geometric complexity of objects would be positive strides in the right direction for the research. Additional research into methods of concrete CNC mold formworks, masonry material composites, and scaled robotic construction of customized geometries would extend the results of this research. On top of that, additional studies in automated design discretization of 3D CAD models would allow for a refinement of the scale, form, and shape of bespoke units for interlocking assembly systems. Discovering novel ways of fabricating non-uniform curvilinear

architectural designs through discrete units and robotic assembly is an expectation of the research. Finally, the research presented in the paper opens the door for the investigations of the structural properties of bespoke architectural units. Through continued study, a distinct language for discretized architectural systems fabricated through robotic means, utilizing unique geometric architectural structures, will emerge, blending construction techniques of the past, present, and future. With these robotic techniques, designers, architects, and builders can advance the field of architectural design beyond manual practices, therefore, accelerating workflows and creating languages of robotically assembly construction.

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