DIGITALLY AUGMENTED MASONRY: APPLICATIONS OF DIGITAL TECHNOLOGIES TO THE DESIGN AND CONSTRUCTION OF UNCONVENTIONAL MASONRY STRUCTURES

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This paper broadly considers the question of linking the representation of a structure to the actual process of physical construction through advanced parametric CAD and digital construction tools and technologies. The intent of this research is twofold: first to develop methodologies to assist architects and engineers working with parametric representations of complex masonry projects such that construction constraints can be used as embedded design parameters during schematic design; and second to explore how digital technologies are able to assist masons during the physical construction of complex masonry walls. This paper is an extension of previous research on masonry design rules and computational representations towards the development of digitally enabled assistive technologies for construction of complex masonry structures.

Keywords: Parametric Modeling, Digital Fabrication, Augmented Reality, Variability, Non-Standard Construction

INTRODUCTION

Digital technologies are nearly ubiquitous in today’s Architecture, Engineering, and Construction (AEC) industry however they have had little transformative impact on masonry design or construction. Although masonry has one of the oldest and richest histories of application in the built environment it is too often seen as a conventional material with limited possibilities in today’s design world of ever increasing complexity. The reality is, however, that with the development of proper methodologies and protocols masonry is one of the most exciting materials to be considered through the lens of digital technologies in design and construction.

Today the question of non-standard construction and formal complexity often implies the use of sophisticated Computer Numerical Controlled (CNC) fabrication equipment to manufacture unique parts in order to construct a complex whole. While this approach continues to be a valid and rich territory for exploration the inverse approach of using standard parts within a complex whole offers another trajectory for designers and constructors to explore. Through
the systematic deconstruction and codification of the rules, or logics, that regulate various material/construction systems we are now beginning to close the gap between the representation and the artifact. This extracted construction knowledge can now be made explicit and can be embedded within intelligent design environments (Parametric Models/BIM) in order to give designers the ability to interactively test high level formal or programmatic ideas against low level material construction possibilities so as to tune design intentions with material realities. Building Information Modeling (BIM) systems are beginning to allow architects to develop constructible complex geometries from both standard and non-standard construction systems while giving engineers and contractors a means by which to calculate, verify, and construct the design. These state of the art design tools are well positioned to have significant impact on the design and construction of sophisticated masonry structures in the near future as Digitally Augmented Masonry (DAM) processes and protocols mature and are adopted into the mainstream of the AEC industry. This paper focuses on how technology can improve both design and construction processes by augmenting and expanding existing conventions in both domains.

DESCRIPTIONS AND ARTIFACTS
The traditional process of interpreting design intent into constructible form has long been established through the system of shop drawings, submittals and specifications. This process of interpretation and translation from the design representation to material construct is a contested space riddled with perceived limitations, miscommunications, and ambiguities. It also represents a vast territory for research in light of the computational tools and technologies that have emerged both in practice and academia. These tools represent an opportunity to bring the representation and the artifact into closer direct contact in the many actualization phases of a project. This problem of translation from descriptions to artifacts is well represented throughout the history of masonry as seen in Frezier’s drawings for a stone stair (Figure 1).

![Figure 1. A.F. Frezier – La Theorie et la pratique de la coupe des pierres (Evans, 1995)](image)

Digital technologies, both representational and fabricational, Computer Aided Design/Computer Aided Manufacturing (CAD/CAM) have been said to allow for a new form of digital craft and user specification through CNC fabrication. This type of purely digital making has been widely researched, practiced, and written about in the last decade however it
is becoming more and more clear that the notion of the purely digital is incongruent with the realities, traditions and possibilities of current construction practices at the scale of buildings. As was the case in computer science the concept of the purely virtual gave way to the hybrid, the blended, the bastardized. The research moved from the concept of Virtual Reality (VR) to Augmented Reality (AR), a form of both/and. Digital making is at a similar intellectual bifurcation. In order to push the possibilities of the digital into the practicalities of the physical a new hybrid approach of Digitally Augmented Masonry (DAM) must be developed which asks first how can the space of potentiality offered by digital technologies begin to learn from, react to, and ultimately transform existing design and making processes that have long historical threads and broad cultural implications. Rather than replacing the mason through automated unit placement equipment (robotics) we argue here that the intuited knowledge which resides inside the mason and is gained through experience is irreplaceable and technology should not try to imitated these highly developed human skills, but rather that technology can assist in tasks where humans are weaker and recede in tasks where humans are stronger.

PARAMETRIC MASONRY REPRESENTATIONS AND METHODOLOGIES

We start from the design side of the process. As in computer programming, there are always several different ways of implementing a solution within a design. One of the major challenges for the development of knowledge-rich parametric models is to find a general and formal method to facilitate the translation of design intent and expertise into a proper set of parametric behaviors. This approach is required because it emphasizes the principle that parametric objects have to be modeled not only as they look but most importantly, as semantic relationships within a specific domain (Sack et al, 2003). To solve this issue we adopted the Building Object Behavior (BOB) description method and notation developed by Lee, Eastman and Sacks (Lee et al, 2003). In our project we adapted this methodology to guide the implementation of parametric behaviors of components and assemblies within the domain of concrete masonry construction (Cavieres et al, 2008). The graphic and abstract nature of BOB representation facilitated the process of collaborative elucidation of structural and constructive constraints which were taken from NCMA design guides. In this manner we were able to pre-tune and guide the parametric definition prior to any software implementation or modeling activity. Such processes allowed us to reduce ambiguity and unnecessary complexity, while providing a graphic specification that can be further re-used and up-dated.

Generative Components was selected as the parametric CAD environment to develop the system for its ease of use, extensibility, and flexibility. In this environment we can quickly test high level geometric concepts against the physical realities of the particular masonry system by propagating discrete masonry units across the surface based on user defined rules (Figure 2). Given the specification of parametric behaviors required by concrete masonry construction the implementation can be set according to the main design intent and system constraints. In Figure 2 we show a case where every block in a course of a wall would be separated from all other blocks based on the curvature of the wall, generating an approximation of surfaces of up to two degrees of curvature. The general technique involves the projection of equal-spaced vertical cross-section lines on the wall surface on 16 in (406 mm) centers. The vertical spacing for the joint beds was achieved by propagation of equal-spaced points along the projected vertical cross-sections on 4 in (102 mm) centers. In this way the specification of both vertical and horizontal spacing for the masonry running bond grid
was satisfied while producing the gaps needed for a particular screen effect (Figure 2a and 2b). For additional information on the representational schema see Cavieres et al, 2011.

Figure 2. Parametric relationships of local objects within global configuration (B.O.B.)

STATE OF THE ART IN DIGITAL MASONRY
Robotic, non-standard bricklaying has been the object of recent research at the Swiss Federal Institute of Technology Zurich (ETHZ), see the recent work of Gramazio and Kohler (G+K). This work is widely known and may be one of the best recent examples of digital robotic masonry (Figure 3). The project described in this paper reflects a similar approach in many regards but also tackles many other issues not addressed in the work of G+K and which restates the value of the mason. The construction of structural masonry at the scale of buildings is still problematic with the fully digital approach. There are two significant problems with the robotic approach and two significant differences between our project and the work of G+K which deal with the interpretation and implementation of construction conventions and structural behavior in masonry. The robotically laid bricks of G+K are essentially glued together, are unreinforced, and deal with relatively small, single story walls. All of these aspects present significant limitations of the G+K system to be deployed as a primary structural system within buildings of any significant size and which must comply with contemporary building codes. Our research begins to deal with these issues by developing a hybrid making system between conventional analog construction methods and digital technology, the DAM approach.
Additional research on automated drone positioning systems is currently in being led by Dr. Raffaello D’Andrea also at the Swiss Federal Institute of Technology Zurich (ETHZ) called ‘Flight Assembled Architecture’ (Figure 4). In D’Andrea’s work intelligent quadacopters are used in conjunction with artificial intelligence algorithms to position masonry units within computationally designed masonry structures (http://raffaello.name/).

Figure 3. Gramazio+Kohler, robotically laid wall assembly & adhesive application process

Figure 4. Raffaello D’Andrea, Flight Assembled Architecture. (http://raffaello.name/)
INTEGRATED STRUCTURAL ANALYSIS AND FEEDBACK PROCESS

From a structural perspective, masonry is well-suited for horizontal curvature – witness Jefferson’s horizontally curved walls at the University of Virginia. To achieve horizontal curvature, each masonry unit can rotate in its coursework a moderate amount from the prior unit while still maintaining its horizontal coursing. Vertical curvature is more difficult to achieve. The traditional method, and the one employed in this project, is through corbelling – that is, the offset of one block relative to the one below it by some limited amount, all while keeping the horizontal coursework flat and level. Tilted masonry coursework has been achieved by Brunelleschi and Dieste, and is a key component in masonry vaults, but generally only works with completely centered or self-stabilizing forms (Dieste, 1992). Another example of this type of masonry construction can be seen in the vaulted work of Rafael Guastavino Moreno as documented by John Ochsendorf of The Massachusetts Institute of Technology.

Two structural analysis techniques have been developed with this method. The first analysis uses a vertical section by section analysis at a given increment along the wall, starting at one end and ending at the other end, treating the wall as a series of discrete members. The second analysis uses the finite element method. For more detail regarding the structural analysis please see Structural analysis and design of non-planar corbelled concrete masonry walls by Gentry et al, 2011.

DIGITALLY ASSISTED CONSTRUCTION METHODOLOGY

The primary construction novelty of this research deals with assistive technologies for spatial positioning of units in complex configurations. The ultimate goal of the research is to develop digital tracking and positioning systems to be used by the mason in the assembly of masonry constructions. As an initial experiment into physical construction of the system we looked to one of the most fundamental masonry construction technologies, the mason’s line. Using the mason’s line as a low-tech analog to a digital vector tools and protocols were developed to assist the mason with the spatial positioning of each unit in the overall configuration. This tool, called the Block Fit Protractor (BFP), is capable of being attached to a masonry unit at the midpoint and then assisting the mason in finding the position of each unit in the overall configuration. The BFP is simple but effective. It determines two degrees of freedom, one rotational and one translational, and in conjunction with the masons line is capable of assisting a mason in the rapid positioning of a unit anywhere in a given XY plane.

As a proof of concept demonstration the research team designed a double curvature block wall for the 2010 National Concrete Masonry Association (NCMA) Expo in San Antonio, Texas to be built by a team of two teenage mason apprentices under the tutelage of their instructor and one the NCMA’s master masons (Figure 5). The design used the DAM system to study the visual, spatial, structural and constructional aspects of five iterations of a wall which transforms from a zero curvature planar condition to a double curvature condition. The shape of the final iteration was a wall that morphs from an S-curve in plan at the base to the same inflected curve at the top with a straight line at the vertical midpoint. Curvature in the wall was accomplished through unit to unit rotation in plan (XY plane) and course to course corbelling in section (XZ plane and YZ plane). The wall was 6 ft (1829 mm) high by 21 ft 5 in (6414 mm) long by 2 ft 8 in (813 mm) wide and was constructed in a variable running bond with 4-hour 4x8x16 CMU (101 mm x 203 mm x 406 mm). The 4-hour block, which refers to
the fire rating of the unit, was selected to increase the face shell thickness of each unit (2 in (51 mm) face shell) therefore allowing for a greater amount of corbelling between courses without the risk of exposing the cells. For further reading on this proof of concept prototype see Al-Haddad et al, 2011.

Figure 5. The Wave Wall: Experimental prototype at National Concrete Masonry Association Expo San Antonio 2010

DIGITAL POSITIONING TECHNOLOGY
Our current research efforts are focused on the development of an integrated digital positioning system which will assist the mason in the placement of masonry units within a complex configuration via a digital tool. This Digital Masonry Locator (DiMaLo) will be able to read the spatial position (unit centroid and vector) of any masonry unit from the design database and through the use of a trilateration technique the tool will be able to direct the mason as to the precise position of the unit within the wall. The trilateration method requires four benchmarks (transponders) from which to sample the distance to the target which can be quickly fit to any standard block once the unit dimensions have been entered into the DiMaLo system (Figure 6). The scenario of use is as follows. The mason would select the unit to be positioned from a graphical display of the overall assembly, clip the target to the unit and begin positioning. The target will give the mason real-time visual feedback as to the X,Y,Z position of the unit and a vector normal to the exterior face shell of the unit. With this real-
time feedback the mason will be able to find the position of the unit in space and set the unit accordingly. Every unit would not require use of the DiMaLo system but rather a sampling of units would be positioned, perhaps every fifth unit in a course, as a lead reference from which other masons can interpolate and infill the units in-between the sampled unit. The complexity of the design would determine how often a unit would need to be positioned using the DiMaLo system.

Today many forms of spatial positioning technologies exist which would be appropriate for development of the DiMaLo assistive technology. Ultrasonic, active and passive RFID’s, computer-vision, and laser tracking systems are all potentially viable technologies for this research. To meet the requirements of the DiMaLo the most suitable candidate of the positioning technology is RFID systems with passive RFID tags (Liu et al, 2007). The RFID reader sends out signals and the passive tags derive their power from the incident RF signal and modulate the backscatter. Each tag contains an antenna and a circuit which would modulate the incident signal in a unique pattern so each tag can be uniquely identified. The operating frequency of a typical RFID system utilized in this type of applications is around 300 MHz – 5.8 GHz which would allow the signal to go through walls and non-line-of-sight positioning. Although the typical reading range is limited (around 2m) and the cost of the readers is relatively high, the cost of the passive tags are low enough to allow every unit in a course to be tagged. Further more, the RFID tags are thin and small in size so they can be easily attached and detached from the unit. The reader has a fixed location relative to every course and is capable of locating the tagged unit with less than 10 cm with the existing technology (Uchitomi et al, 2010). The accuracy can be improved much further to have error within 1 cm with complex sensing schemes such as the use of reference tags (laid out as fixed grid in a course) and inter-tag spacing (Manzoor et al, 2010). In addition, the antenna of the tag can be made directional so that the orientation of the tag can be identified such as the use of patch arrays (Coutts et al, 2006). Therefore, as the tag is attached to the exterior face shell of the unit, the vector normal to which can be estimated along with the 3D position of the unit in the course.
CONCLUSION
Ultimately this research hopes to give architects, engineers, and constructors new tools and methodologies to expand the formal and compositional possibilities of existing construction systems in an intelligent and responsible way. The construction system described above was an interesting and enlightening first pass at the question of physical construction however current and future research questions are focused on the use of digital positioning systems which will drive the DiMaLo system. The integration of schematic design tools, structural simulation schemas, and physical positioning systems is the major challenge moving forward.

Additionally, future research will focus on the refinement of both the structural analysis method and the BOB implementation in order to create a valid tool that all the players of the design and construction process can easily and intuitively understand and creatively use.

The gap between digital design representations and physical constructs continues to contract as new and novel methods for interrogating the relationship between existing construction industry conventions and new modes of practice develop. Questions of how and where digital tools will fit into an industry as enormous and complex as that of the AEC world are only beginning to be formulated. The promise of fully automated, self constructed buildings may or may not come to fruition but in the meantime hybrid Digitally Augmented Masonry methods will fill the void of this possible future.
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REFERENCES


