Control and Collaboration: digital fabrication strategies in academia and practice

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The integration of digital tools currently being used in many schools and offices with Computer Numerically Controlled (CNC) hardware, has allowed architects to exert a far greater degree of control than they have previously been afforded. It is precisely this control that enables greater collaboration during design phases between architects and fabricators. However, the impact of this integration on academia and small practice is unknown. Several questions remain to be answered regarding teaching fabrication techniques and identifying strategies suitable for adoption in small firms. This paper investigates digital fabrication not as a software-specific set of capabilities, but as a design methodology that can allow schools to graduate young practitioners who can use these concepts to design and manage projects in more sophisticated ways. We outline six control and collaboration strategies and present several projects that explore those concepts through analog, digital, and hybrid methods.
1. INTRODUCTION

It is generally agreed that the architectural profession has entered into a time in which digital design and fabrication technologies play an important role in the realization of built work. In this age of digital fabrication, the idea of production can generate new architectural effects that are exposed through the intersection of form, material, and technique. These effects can result in a variety of conditions including the mixing of complex programs to the cost savings passed on to the client through a more efficient construction process.

Architects have started using these technologies to interface their digital data with the computer-controlled production capabilities of contracting firms, creating a new set of assemblies and products. Such processes are one way that a more refined digital model, free of representational annotation, can be used to more fully investigate virtually the impact and sequencing of fabrication and assembly in a project. Problems that had traditionally been encountered in the field, causing added expense and time delays, can be vetted on the design side through the multiple iterations architects and their consultants engage in during the design of a building. Larger firms have utilized such technologies for some time, and we have seen how a more integrated design/construction process has yielded unique products. Such an actualization process allowed the newly opened Denver Art Museum, designed by Studio Libeskind and constructed by Mortenson, to be completed three months ahead of schedule with no field change orders [1].

While the applicability of computer-controlled manufacturing technologies has been successfully proven by large, established firms executing complex projects with big budgets, its utility in small offices working on small to mid-scale projects is as of yet unknown. The U.S. Department of Labor documented in 2004 that the majority of architectural practices in the United States are considered small firms (See Note 1), and the American Institute of Architects estimates that over 65% of AIA members were associated with firms of 5 or fewer people (See Note 2). Alejandro Zaera-Polo, whose firm completed the Yokohama Port Terminal, has already written that innovation occurs many times by amateurs who have no concept of their own limitations, as opposed to the more comfortable and seasoned experts who know what they can deliver [2].

The promise of these technologies, however, is not to allow architects to make buildings more consistent with the aesthetics of Frank Gehry. Rather, these technologies bring the opportunity to allow architects to regain control over the construction process by presiding virtually over a series of assembly methods generally left to contracting counterparts in the field. We posit that such control streamlines collaboration and encourages further iteration during the design phases of a project.

Small firms, with their uneven payrolls and small staffs, could benefit...
greatly from the utilization of these technologies; and some have. This has been less from the acquisition of high-end software packages and computer systems and more from the innovative thinking that is necessary for less-experienced practitioners to get things built. An immediate advantage to engaging digital fabrication strategies in small projects is that potential liability associated with increased collaboration are reduced due to the scale of the project. While beyond the scope of this paper, the issue of liability is one that deserves serious consideration as the profession moves towards formalizing these working methods. This paper will demonstrate examples of utilizing digital fabrication strategies to produce innovative designs at smaller scales and on tight budgets.

We have found several control and collaboration strategies that are commonly deployed by forward-thinking educators and practitioners. These strategies span issues of software and hardware use, organization and translation of data, and material considerations in both virtual and physical environments. The six strategies below are derived from the projects we illustrate here. We posit them as guidelines for teaching and deploying digital techniques and fabrication.

**CONTROL AND COLLABORATION STRATEGIES:**

1. Geometry is created as a shared 3D virtual as opposed to a set of annotated drawings.
2. Geometry is rule-based and parametrically constrained, so as to encode materials and assembly methods.
3. Geometry is linked to an integrated database, so as to enhance collaboration.
4. Geometry is rationalized, segmented, and ordered for physical assembly.
5. Geometry is sent directly to Computer Numerically Controlled (CNC) hardware for manufacturing.
6. Geometry is translated and transferred digitally, thus avoiding interpretation errors.

Each of these strategies involves the further communication between the architect and others. These help the architect to maintain control of original design intentions while fostering collaboration within a digital environment.

In most cases, the software and hardware utilized is consistent with the tools used today in firms and many schools of architecture, including 3D modeling software and CNC hardware such as a laser cutter and 3-axis router. Some of the projects shown here utilize techniques and procedures that are essentially embedded in 3D modeling software but have used them in an “analog” manner. The results have been innovative, albeit smaller-scale, built projects. These procedures have made clients and fabricators/contractors more comfortable with what may have originally been seen as untested ideas with regard to building.
2. PARADIGM SHIFT

Before specifically citing these innovative procedures and techniques, it is important to establish some of the thinking that has led to this paradigm shift in design and fabrication. The writer Manuel DeLanda poignantly differentiates two distinct design methodologies utilized in schools and practices today. He contrasts a "cerebral" methodology, one in which a form is generated as an immaterial thought process awaiting the application of a material, with one that as its essence takes into account a philosophy of materials [3]. Such a philosophy is consistent with a change in the traditional format of architectural delivery: the possible to the real to a new and seamless one: the virtual to the actual. In the former paradigm, architects prepare a two-dimensional hard copy set of documents that were representative of a possible building. They transmit the documents to a contractor for costing and construction. The contractor in turn interprets these drawings, building from them a possibility that may not consistent with the designer’s original intentions. The former paradigm privileges interpretation, while the new privileges translation. In this paradigm, architects work with fully developed and precise virtual constructs that only need be actualized through translation to another medium (a CNC router, etc.) [4].

For Sanford Kwinter, “the virtual, though it may have no actuality, is nonetheless already fully real.” [5]. This is not to suggest that contractors will no longer be needed in the actualization process, but through a more precise means of translation (actualization), building components can be more consistent with the designers’ original (virtual) intentions.

The understanding of material and construction processes, so critical in the history of architecture, has been distanced in contemporary training. It can, however, find its way back into the architect’s work by way of digital methods that take into account fabrication processes. Through precision in the creation of digital models and control over their translation, designers can understand implications of material choices and assembly methods. Such design and production methods also permit the ability for data sharing through a single model with others. Whether actualization occurs through data transfer to a CNC machine or via a traditional building process, the fluidity of the procedure positions the architect less as a consultant and more as a manager of design information.

3. PROJECTS

We will show here a series of academic and professional projects that we have undertaken through digital, analog, and hybrid methods. In all cases, the projects illustrate the eight control and collaboration strategies (CCS) articulated above (See Note 3). These projects support the virtual to actual paradigm while at the same time increasing the rigor of the designed object. While the projects vary in size, they illustrate processes that are scalable and translatable.
3.1. Academic Projects

Digital fabrication technologies have been tested at the School of Architecture at the New Jersey Institute of Technology (NJIT) through both design studio and seminar work. In each case, virtual procedures and the ability to generate material and spatial effects have been privileged over the representational capacities of the computer.

Command POD (2005)

All students at NJIT are required to complete a “comprehensive” studio in the final semester of study in which a set of technical documents is produced. While many of these are traditionally executed, a comprehensive studio given by Richard Garber in the spring of 2005 challenged students to work and think within the virtual to actual paradigm. Students were given access to the newly formed fabrication laboratory (FABLAB) and an assortment of digital technologies that were associated with it.

In response to the tsunamis that hit Southeast Asia in December 2004, students were asked to design rapidly deployable permanent structures that served housing and/or medical functions. By asking the students to consider rapid deployment, and modeling strategies that moved beyond Computer-Numerically-Controlled fabrication, it was possible to consider construction sequencing (CCS 4: rationalized for assembly). The Command POD was developed as a series of modules, each devoted to a program for “living” (e.g. eating module, sleeping module, etc.) (Figure 1). The modules were constrained in their overall size so they could be fabricated off-site and easily trucked or flown in (CCS 2: rule-based, constrained geometry). The exterior form was designed to respond to prevailing winds at a chosen site (Figure 2).
The assembly process was derived from contemporary ship-building techniques, in which boats may be constructed in different ship-building yards by sharing a common data set (CCS 3: integrated database). The structure of each model would be cut from 1/2” plywood sheets that are built-up by gluing and screwing so that a 1 1/2” U-V rib system that responded to the building’s exterior form could be developed and fastened through notching (See Note 4) (Figure 3). The structural shapes were nested to 4’ x 8’ sheets of 1/2” plywood, which allowed each to be cut on the school’s CNC router, which has a 48” x 96” bed (CCS 5: geometry for CAM) (Figure 4).
To clad the structure, three layers of wood slats were lapped across it, which were also cut to length and specific shape where necessary by translating data from the virtual model. These slats were conceived as developed surfaces in Rhinoceros 3D which allowed us to unroll them to a flat pattern, much like a fabric pattern (Figure 5). A developed surface is curved in only one direction so templates can be easily produced (CCS 2: rule based geometry for assembly). This is similar to aligning a planar surface to a coordinate plane (e.g. X-Y-Z). However, the program uses an algorithm to calculate the flattening within a prescribed tolerance for fabrication. The sheathing is also nested to plywood and cut on the router. Once this sheathing is attached to the structural frame, a series of fiberglass layers are applied to make the building waterproof, much like a boat hull.

Additionally, throughout the semester the project was consistently presented to critics as a virtual model projected through an XGA projector. The model was ordered so that all building systems were layered, allowing them to be toggled on and off for a real-time understanding of systems integration.

The project was also successful as an information model by integrating building systems into its design process during schematic design. By modeling each component precisely, including a schematic mechanical and plumbing system, building integration was successfully understood virtually (Figure 6). This integration through design development allows for multiple

Figure 4. Image of scaled model, constructed of 1/16" chipboard and Z-Printed tripod supports.

Figure 5. Sample of nested drawings of structural ribs to be milled from 4' x 8' plywood sheets.
iterations of building system alternatives so that associated design considerations can be tested before making final decisions about form, materials, and specific building equipment. By vetting such conditions on the design side, costly errors in the field can be avoided and construction sequencing can be more comprehensively thought through.

The Command POD illustrates how a digital modeled designed for assembly with the control and collaboration strategies facilitates collaboration and heightens awareness of material properties. Because the design was understood as a series of components that would be cut from standard plywood sheets, the student was challenged to consider the efficient use of the regulating sheet size and thickness and apply that knowledge to all design and assembly considerations. Additionally, the experience of systems integration, fabrication, and assembly brought forth issues that otherwise would not have been addressed if digital tools were used solely in a representational mode. This process was also consistent with the design methodology outlined above that utilizes a philosophy of materials from the outset of the project.

**Digital Tectonics**

A seminar titled Digital Tectonics, taught by Wassim Jabi, investigates the relationship of digital tools and architectural tectonics [6]. In the projects presented here students were asked to design and construct a 10"x10"x10" physical cube (Figure 7). The students were asked to comply with several requirements:

- The cube must clearly define the corners as joints, the edges as linear elements, and the surfaces as cladding.
• The cube should be capable of assembly and disassembly.
• The cube should aspire to the purity and perfection of an ideal cube.
• The cube should take into account craftsmanship and the requirements of efficient production.

To evaluate the cubes, three criteria were measured: the time it took to assemble the cube; the number, proportion and size of the cube’s components; and the overall accuracy, quality and craft of the cube. These were important criteria to evaluate as they have a direct relationship with processes commonly found in larger scale work.

By requiring the students to assemble and disassemble the cube, they naturally had to keep track of the various component parts (Figure 8). When they modeled their cubes digitally, students created a 3D database of parts that corresponded to the physical construction (CCS 1, 3: integrated database for collaboration & assembly). In order to achieve the highest score, the cube would have been made of many pieces that could be assembled quickly. While this may not have a direct correlation to a real-life situation, it does require the students to consider alternatives and study ways to increase the efficiency and construction sequence of their design proposal (CCS 4). The resulting physical cubes illustrate an interest in geometry.
assemblies of material, opacity, and connections. The cubes varied in fit and trim quality due to the varying degrees of student skills and familiarity with the chosen material. The most successful cubes tended to be those sent to a laser cutter for component manufacturing (CCS 5).

In the second phase, the students were asked to choose a portion of an object that they found intriguing and look for repetition, pattern, and rhythm. They were then asked to invent a method to scan this object or trace its dimensions, create a 3D model of the object, and re-interpret this object as a rhythmic entity that can be understood as architecture (Figure 9). Finally, they were asked to rationalize the 3D object through segmentation, tessellation, slicing or other similar processes, to subdivide the object into multiple 3D surfaces that can later be re-assembled, and to use the laser cutter to cut those surfaces (CCS 4, 5). The process of slicing and producing 2D templates automatically led to an understanding of material cost estimation and waste reduction. These small-scale issues directly scale up to real-life construction projects.
The Digital Tectonics projects illustrate by using the control and collaboration strategies that rationalized, systematic geometric models create better components for assembly. Additionally, they encourage the students to investigate translation from the physical to the digital and vice versa. Because the cubes designed in first project were first built physically and then digitally inputted into the computer, students better understood material and assembly issues than if they had started with an abstract and purely representational digital model. That is, regardless of the modeling technique, the basic conception of the project was derived through an investigation of materials and physical assembly issues rather than from manipulation of digitally created forms. This process is not unlike a working method utilized by Gehry Partners. Many of their rationalized digital models are derived from 3D scans of physical counterparts [7]. The second project, conversely, challenged students to manufacture a digitally created geometry providing them with valuable experience in the rationalization, tessellation, translation and physical assembly of digital data.

3.2. Professional Projects

The two projects shown in this section merge digital and analog production techniques to produce a highly specific and differentiated product. Both projects had comparatively small budgets, and were produced by small, young practices (at the time). Each was innovative in its production techniques, as in many cases such techniques were presented as alternatives that allowed for time and cost savings. From intimate involvement in design through fabrication, we can describe the design approach, software utilization, and fabrication techniques.

In The Tube (2004-2006)

In the Tube is a ground up 2,200 square foot house located a quarter of a mile from the Atlantic Ocean in Bradley Beach, New Jersey, designed by GRO: Garber Robertson Office (Figure 10). As such, it was designed to maximize living space on a small site and have optimal views to the water. Bradley Beach is made up of small lots, so is relatively dense for a beach town, and privacy from neighbors is an issue.

To modulate openings and natural light and use a typology found in abundance at the beach, the dune fence, GRO designed the facades as a series of rolling 2x12 slats that formally transitioned between cantilevered areas of the house and provided enclosure for the main entry stair (Figure 11). As the project developed, the variety of lengths and angles of the varying slats proved very difficult for the general contractor and his small crew of framers to build on site. Each slat is unique in angle and length, so GRO used parametric software to catalog each condition and develop a custom “slat hanger” for each, orienting them as flat to the X-Y coordinate plane (CCS 2) (Figure 12).
The notion of measuring during the construction and fabrication process has traditionally been one of sometimes spirited exchanges between architects, general contractors, and their sub-contractors who do the fabrication. As Chuck Eastman writes, “The easy, close-working relationship between designers and builders has been largely disappeared. The easy mapping between an architect’s intent and its realization by a builder cannot
be assumed.” Shop drawings are usually sent back and forth between all parties until an agreed-upon reality can emerge from the architect’s drawings (possibilities in the old paradigm). Many of these fabricators who produce products for smaller-scale projects still work by hand, drafting fabrication details with data provided by the architect through drawings. This is a third layer of interpretation brought to the traditional building process. GRO sought to bypass this condition by removing field measure from all but straight members in the construction of the east and west façades. Rhinoceros 3D was used to create a virtual model of the house and specifically its façades. The architects then transmitted the necessary data digitally to a fabricator who would cut each of the 24 hangers from 1/4” stainless steel on a laser cutter and fold them using a brake (CCS 4, 5, 6: rationalized geometry controls manufacturing & eliminates errors) (Figure 13).
The hangers were designed so that a pair (left and right) would support, through mechanical fastening, the joint between an angled and vertical slat. Once each angle was determined, a template model was created and then exported as a 2D vector drawing to AutoCAD. Each left and right hanger was 1 5/8” wide, to accommodate the width of a 2x12 wood joist, and 36" long, so that 18" of the hanger could be used to support each of the angled and straight slats it would bring together. Additionally two 4” wide tabs were designed as part of the template. These were folded at 90 degrees to provide a fastening surface to the wide part of each 2x12 wood joist (Figure 14).

The general contractor only required a lumber cutting schedule and the fabricated slat-hangers (CCS 3). This process greatly streamlined the fabrication process of the façades, providing a more efficient means of construction while saving the client additional labor costs.


A-Wall is a 200 square foot (20’ x 10’) display surface completed by SHoP Architects, PC in 2000 for Architecture magazine. Though this project has been published in the past [9], the procedural steps (in both design and fabrication) are important in demonstrating the necessary shift in design thinking that is critical in the virtual to actual paradigm. The project was also important in establishing analog operational procedures that are still evidenced in the firm’s current and more sophisticated digital operations.

A-Wall was created using the NURBS modeling environment in Maya to...
virtually produce a series of display shelves that peel from its main surface (CCS 1: 3D virtual construct). In addition to providing such display area, the wall had a series of additional requirements: it needed areas for signage, had to be modulated so that it could be completely dismantled and put back together by a team of two, and had to be designed and constructed for $20,000 (Figure 15). As opposed to understanding this as limiting the project’s effects, these constraints were viewed positively by the firm and a decision was made to explore virtual and CNC fabrication possibilities while manually fabricating certain parts.

Figure 14. Catalog of varied slat-hangers.
Once the wall's surface was articulated in Maya to satisfy programmatic requirements, the surface was exported via Maya's DXF translator to AutoCAD. This step utilized a polygonal algorithm that tessellated the smooth NURBS geometry (Figure 16). This tessellation was accepted as the instantiated final geometry of the wall surface. When opened in AutoCAD, the wall surface existed as 496 unique, triangulated shingles ranging in size from about 4" to 18" in length (CCS 6: digital translation reduces errors) (Figure 17). As a fabrication scheme had yet to be resolved, this translation process allowed the design team to contemplate the laser cutting of each of the shingles and their connection to a substrate attached to a series of vertical supports that would be manually cut from plywood.
After consulting with a roofer about the fastening of the triangle-shingles, each of the planar geometries was aligned to the X-Y coordinate system in AutoCAD and two additional tabs were manually added to each shingle polygon. These tabs were the portion of material that would be screwed to the wall’s substrate, which was wiggle-board, a type of flexible plywood. Each triangle was also numbered, and each number would be scored into the cut shingles as a way to sequence the construction (CCS 4) (Figure 18).

TIMET, a sheet titanium manufacturer was gracious enough to donate to the firm for this research endeavor 8 sheets of 18 gauge material, each 39” x 96” in length. As the amount of sheet material would be just enough to cut each of the 496 triangle-shingles, a very careful manual nesting of all of the parts needed to be undertaken (CCS 4). While there are now plug-ins for various software packages that will efficiently nest shapes for template cutting, each shingle was manually placed on a virtual sheet using only offset rules of thumb by the laser cutting shop (Figure 19). While this “hand and eye” approach predates automated procedures now available to architects, such manual processing is critical to a holistic understanding of many digital fabrication principles. The nested files were e-mailed from New York to a Long Island laser fabricator for cutting (CCS 5, 6).
A contractor close to the firm at the time estimated that the wall would have cost $80,000 USD for a general contractor to build from a traditional set of drawings, while the virtual processes the firm undertook combined with both manual and automated fabrication allowed the project to be constructed for about $20,000 USD - a 75% difference from the contractor estimate (Figure 20).

Figure 19: Nested shingles on 96” x 39” sheets.

Figure 20: A-Wall completed fabrication detail.
While this project represents a more manual approach to extracting and nesting component geometry, an identical result can be achieved through a more streamlined digital process aided by new software tools. Software packages have always been able to rationalize NURBS surfaces as a series of tessellated polygons (Figure 21), but more recently, tessellated geometry can be imported into fabrication-interface software, such as Lamina by LaminaDesign. Such software allows component parts to be automatically extracted, numbered, and nested in preparation for CNC cutting (Figure 22). This package can import 3D geometry in a variety of file types (e.g. 3DM, 3DS, OBJ, STL), allow the user to specify a fabrication method and material, subdivide the object into component surfaces, and prepare a series of numerically-taged profiles ready to be cut on a CNC router or laser cutter (Figure 23).
While A-Wall was relatively small in size, it proved to be significant in establishing protocols for digital fabrication and modeling techniques used currently in SHoP’s larger work. The project illustrated five of the six control and collaboration strategies and some, such as CCS 4: the rationalization and ordering (nesting) of 3D geometry, were undertaken through a manual means in AutoCAD. This suggests that processes now streamlined through software such as Lamina were embedded as design techniques within the firm’s working process. SHoP gained valuable insights with regard to rationalization, translation, and assembly steps through this manual means of organizing digital data. This has ultimately allowed the firm to utilize such processes in the design and execution of larger projects such as the Porter House, a residential development in New York, and the Camera Obscura at Mitchell Park in Greenport, New York.

Figure 23. Example of a Lamina cut sheet.
4. CONCLUSION

The advent of automated manufacturing processes and the possibility of directly translating virtual creations into physical artifacts have piqued the interest of educators, students and practitioners in architecture. The combination of digital tectonics and fabrication technologies allowed designers to conceive of buildings as assemblages while celebrating their structural clarity, materiality and detail. Furthermore, it brought forth the possibility of remaining true to the tectonic tradition while addressing the shifts in culture and media towards the digital.

The work presented here identifies production trends toward more sophisticated parametrically-controlled software such as Gehry Technologies’ Digital Project or Autodesk’s Revit. While each of these systems control geometry through complex algorithms or scripts, at their base, they share the six control and collaboration strategies that have been outlined here. Such software would have allowed for a more streamlined execution of the presented projects. However, each of the projects demonstrated a design philosophy of materials that is a critical prerequisite to the integration of digital fabrication technologies in the creative process. The case studies indicate that imparting to students methodologies founded on control and collaboration strategies, a concern for tectonics and materiality, and digital production methods is more useful than engaging them in the peculiarities of a specific piece of software. The adoption of these tactics has allowed educators and students to more thoughtfully incorporate material and production issues in the architectural design process, which in turn has graduated young practitioners that challenge traditional design processes and construction methods.

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Notes

1. Architects held about 129,000 jobs in 2004. Approximately 3 out of 5 jobs were in the architectural, engineering, and related services industry-mostly in architectural firms with fewer than five workers. See http://www.bls.gov/oco/ocos038.htm for further information.
2. See http://www.aiaatlanta.org/members/index.cfm?Fuseaction=SmallProjects&menuval=members
3. Where a project illustrates a control and collaboration strategy we note this in the text as (CCS n) where n is the strategy number.
4. U-V coordinate systems are used to locate isoparametric geometry in non-planar surfaces.

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