Visual-Physical Grammars

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***Abstract*—This paper describes a proof-of-concept study for a new kind of formal grammar – a *visual-physical grammar.* Visual-physical grammars are generative descriptions for the design and manufacture of building assembly systems that provide economical, visually rich, and structurally sound design variations for houses and other small structures. The building systems are aimed for communities in developing parts of the world, and incorporate decorative, vernacular design styles. A visual-physical grammar specifies the full-scale details of assemblies with rules that generate complete CAD/CAM data for fabrication. This paper reviews a pilot study for an automated, visual-physical grammar for an assembly system based on a vernacular language of Greek meander designs. The stages of the study from the development of the grammar to the full-scale construction of a wall section are discussed. The results demonstrate the potentials for embedding visual properties in structural systems through the integrated use of grammars and digital fabrication.**

***Key Words*— building assembly, digital fabrication, housing, shape grammars**

I. INTRODUCTION

This paper describes a proof-of-concept study for a new kind of formal grammar called a *visual-physical grammar*. Visual-physical grammars are generative descriptions for the design and manufacture of building assembly systems that provide low-cost, high-quality, visually rich design variations for houses and other small structures. The building systems are aimed for cultures and communities in developing parts of the world, and incorporate vernacular or other decorative styles into their design. A visual-physical grammar is comprised of rules that specify the full-scale visual, structural, and material details of the components of a building system, and the different ways components can be assembled. The rules apply to generate a *visual-physical language* of assembly design alternatives. Encoded as automated software, the grammar generates complete CAD/CAM data for the digital fabrication of components and their assembly.

This work is motivated in part by the urgent, global need for economical, quickly manufactured housing in developing parts of the world, in rural or underserved communities, and in post-disaster environments. Developing communities often have strong visual, vernacular traditions that are expressed in artifacts at all scales from utensils to clothing to houses. These traditions have important cultural and social functions that promote community identity. Too often, though, low-cost, prefabricated, or emergency housing solutions are generic and bland, ignore local design traditions, and are devoid of cultural sensibility. The research described here may lead to innovative new solutions for housing which not only provide shelter but also support important cultural values through the integration of familiar visual design features.

Two complementary areas of design computation are brought together in this research: shape grammars and digital fabrication. The visual, aesthetic aspects are developed through shape grammars [1], [2]. A shape grammar is a set of visual rules that apply recursively to a starting shape to generate a language of designs – that is, a set of design alternatives embodying a particular style. The structural and material aspects of the research are developed from current research on mono-material assemblies with interlocking components that can be fabricated with CNC machines. Components can be assembled by hand on-site with few tools and without additional binding material such as mortar. These physical aspects of the research are developed in a manner similar to physical design grammars [3].

We explored the potential of visual-physical grammars through a specific, proof-of-concept study: an automated visual-physical grammar for a wall assembly system based on a vernacular language of complex, ancient Greek meander designs [4]. This vernacular language is no longer being practiced. However, the intent of this exploratory study was to determine if and how a visual language could be incorporated into a grammar for an assembly system. The study had four phases of development and testing. First, a visual-physical grammar for an assembly system for walls exhibiting meander patterns was developed "on paper". Second, the assembly system was digitally modeled and physically prototyped at different scales. Third, the "on paper" grammar was automated to generate complete CADCAM data for fabrication of assembly variations. Fourth, a representative section of an assembly – a corner wall section – was constructed of concrete at full-scale. These four phases were cyclical and overlapping: work in each phase was often concurrent with, or entailed refinement of, work in another phase.

In this paper, we overview the four phases and conclude with findings, contributions to the field of design computation, and future directions for this research.

II. GRAMMAR DEVELOPMENT AND TESTING

Phase One

We began with a shape grammar for a language of Greek meanders. The grammar generates meander variations by stacking and shifting rows of connected S-shapes (Fig. 1).

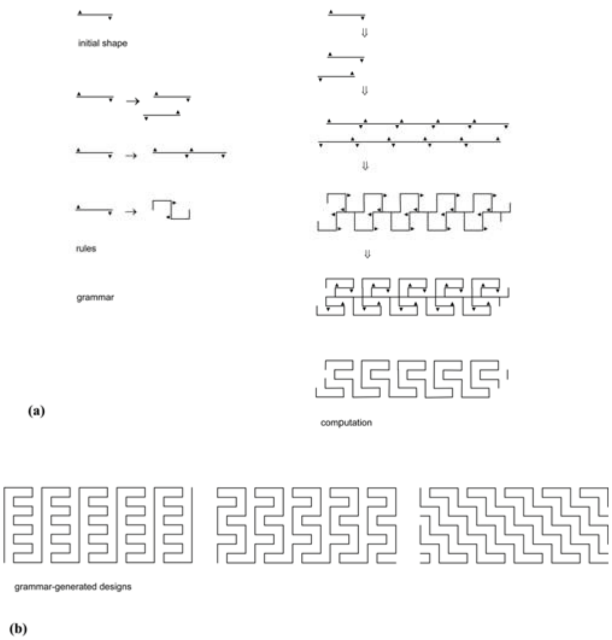


Fig. 1. (a) An excerpt from the Greek meander shape grammar and a computation of a meander design. (b) Some designs generated by the shape grammar.

We translated this two-dimensional grammar into a three-dimensional grammar, on paper, that generates a language of "meander-walls", that is, walls with elevations that express meander patterns. The meander-walls are intended to be the structural envelopes or walls of small buildings. The elements of the grammar are three-dimensional "meander bricks" – the components for a concrete, double-wall assembly system. There are two main, repeating components which come in two colors and create the main, overall wall patterns. There are also a number of specialized components for terminating the patterns at the boundaries of walls. The components have integrated aligners so that they can interlock securely both horizontally and vertically to form stacked "meander courses" without the use of mortar (Fig.2). The components were dimensioned to satisfy both visual and physical goals. They combine to create meander patterns at an aesthetically pleasing scale and they are an appropriate size for lifting and placing by hand.

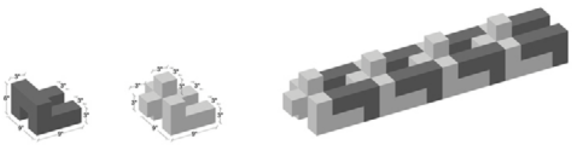


Fig. 2. The two main meander components and a meander course.

The rules of the grammar specify the different ways that the components can be assembled to generate different kinds of wall structures with different meander pattern variations. (See Fig. 4, next page.) Wall structures generated by the grammar include four-sided enclosures and orthogonal, non-intersecting wall structures with any number of sides – for example, free-standing walls, L-shaped walls, U-shaped walls, right-angled zigzag walls – all with window or door openings (Fig. 3).

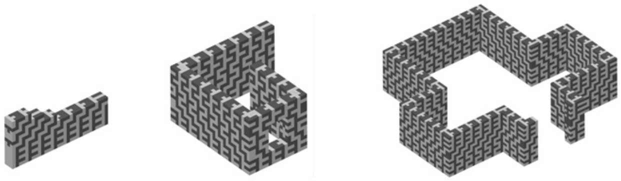


Fig. 3. Sample meander-walls generated by the visual-physical grammar.

Phase Two

Concurrent with, and following, the first phase, we developed and tested the structural and material aspects of the grammar components and their assembly. This involved digital modeling and then physically prototyping at various scales. Notably, we developed an innovative technique for digitally fabricating molds for the concrete components. The molds are made of layers of CNC-cut rubber sheets set within plywood, rockable "cradles". Each cradle holds two to three molds for components. The cradles can be rocked by hand or by foot as the concrete mix is poured in to facilitate the distribution and settling of the mix. The modeling and testing of components and their assembly was a multi-stage process, including:

a) Virtual modeling of components and their assembly in CAD to test the visual aspects of the assembly system and compliance of assembly variations with the original shape grammar.
b) Physical prototyping of components with a layered manufacturing machine at desktop (1:6 scale) to test the physical assembly of components (Fig. 5).

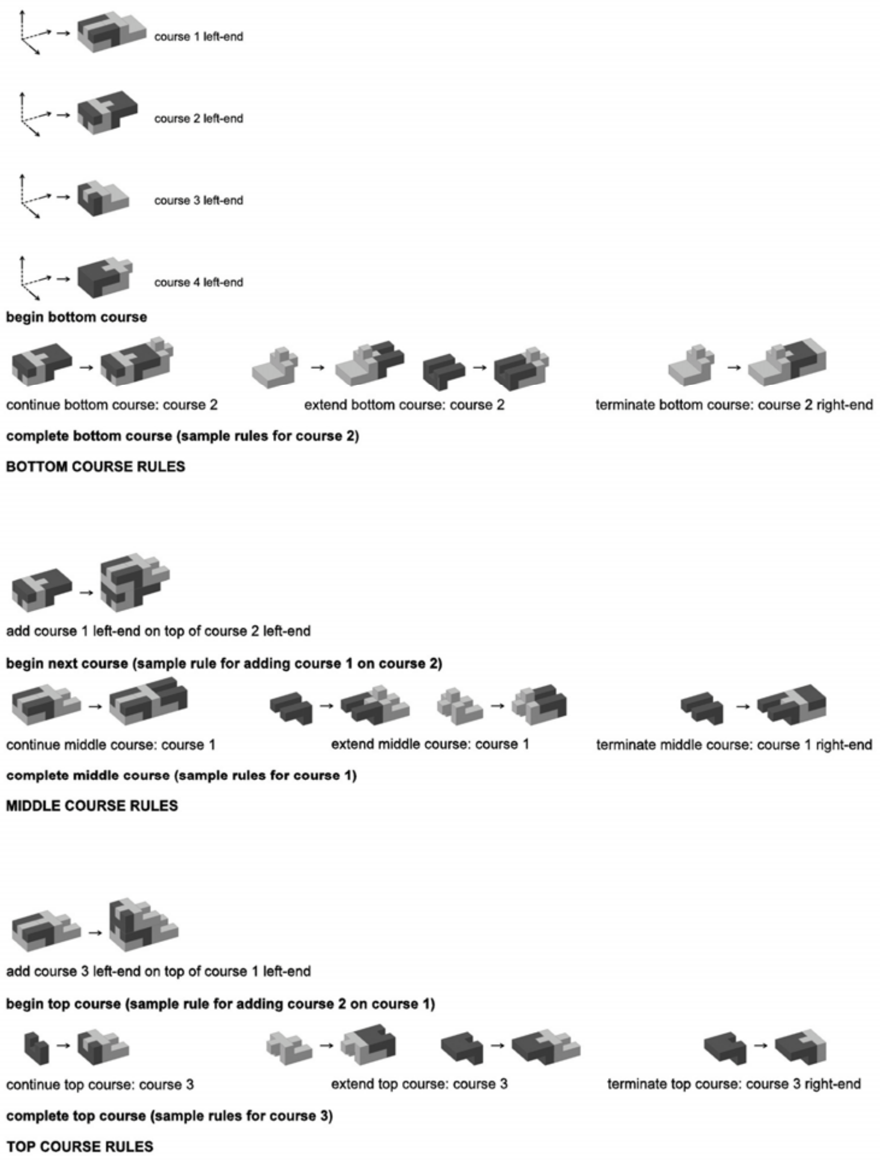


Fig. 4. Sample visual-physical grammar rules.

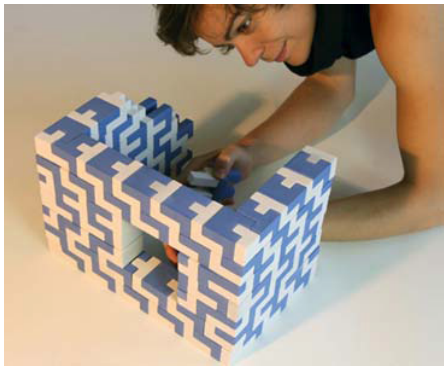


Fig. 5. A prototype 3D-printed wall assembly.

c) Physical prototyping of components cast using laser-cut layered molds at 1:4 scale to test our novel, digital mold-making technique (Fig. 6).

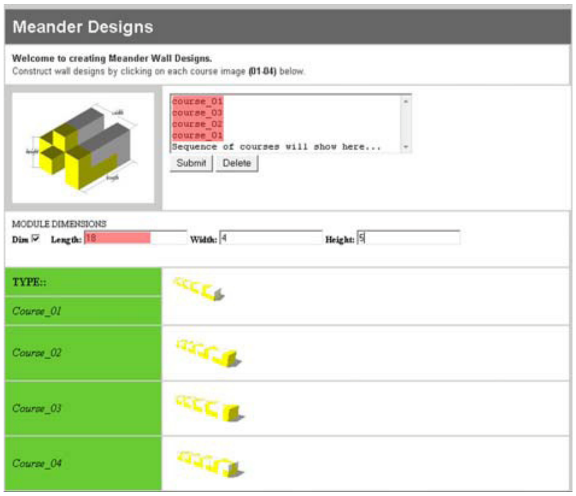
Fig. 6. A prototype laser-cut mold-making device with cast components.

d) Physical prototyping of components cast with CNC-cut layered molds at full scale. Here, we determined that the meander bricks could be cast relatively quickly and precisely by one or two people (Fig. 7).

Fig. 7. Physical prototyping of CNC-cut layered mold system and casting of components.

Phase Three

The "on paper" visual-physical grammar was automated using Ruby, JavaScript, and HTML on an Intel Duo Core CPU @2.00GHz on a 32-bit operating system. The program generates CAD/CAM data for the full-scale fabrication and assembly of all the meander-wall variations generated by the on-paper grammar, with the exception of openings, which we are continuing work on. The program interface allows users to control visual and physical criteria, including the configuration and dimensions of a wall structure and the choice of a meander pattern for it (Fig. 8).



Welcome to creating Meander Wall Designs.
Construct wall designs by clicking on each course image **(01-04)** below.

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course_01
course_03
course_02
course_01
Sequence of courses will show here...
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MODULE DIMENSIONS
Dim ☑ Length: 18 Width: 4 Height: 5

Fig. 8. Sample user interface for the automated visual-physical grammar.

The output of the grammar provides different functions for the designer (or potential occupant), the fabricator, and the builder of a wall structure. It includes:

- a 3D visual representation of the generated wall structure to show how the meander pattern looks (Fig. 9).

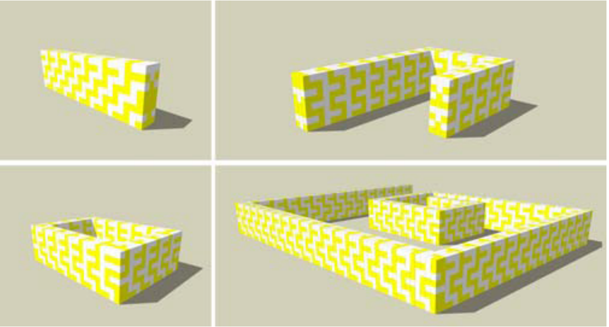

Fig. 9. Sample meander-walls generated by the automated grammar.

- an Excel spreadsheet indicating all the needed components for the wall, and a production schedule for manufacture and assembly given a user-defined completion date (Fig. 10).

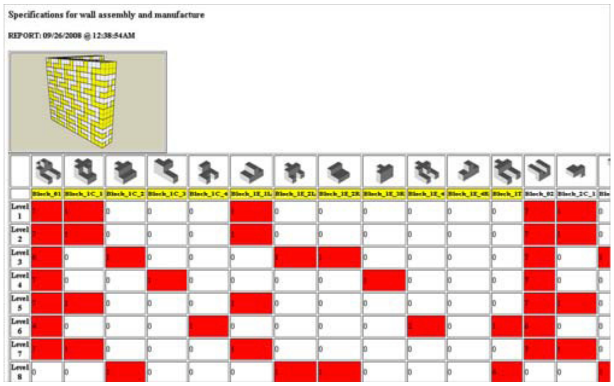
Specifications for wall assembly and manufacture

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Fig. 10. Excel spreadsheet giving the block inventory for a meander-wall.

- a visual assembly guide or diagram with each meander course shown separately.
- a digital file specifying all the cut sheets for the layered molds for wall components. This file is the input to a CNC machine which cuts the mold layers automatically.

Phase Four

While developing the automated grammar, we began testing its output by generating the design and CADCAM data for the manufacture of a corner wall section at full-scale. The wall had two sides, each with a window opening (Fig. 11). The wall was 7 ft high. One side was 8.5 ft long at the base with an unfinished, staggered side to show the components with an unfinished boundary. The other side was 4.5 ft long. The wall had a total of 265 blocks. The production schedule for the wall was guided by our program, and construction was accomplished over the course of a few weeks.

Figure 11. Full-scale corner wall mockup.

III. FINDINGS

Our work demonstrated well the feasibility of our goals, particularly the real-world potential for designing and building homes using formal grammars combined with digital fabrication. In particular, we conclude that it is possible to define generative descriptions for the full-scale manufacture of building assembly systems that integrate vernacular pattern languages.

The vernacular language we worked with was very specific. For this language, it was straightforward to translate the main elements of the shape grammar into structural building components. However, we also needed specialized components to cap or bound the sides, tops, and bottoms of walls and wall openings, and specialized components to turn corners, all with the aim of continuing the overall pattern or terminating it in a visually pleasing way. The design of these specialized components was not straightforward, and we expect that this may be the one of the more challenging parts of the development of any visual-physical grammar for an assembly system.

It was also straightforward to automate the visual-physical grammar. The initial output of the grammar is a set of building components for the user's selected wall variation. This initial output was then translated into CAD/CAM files for the negative shapes, that is, the layers for molds for the cast components.

The construction of the full-scale corner wall allowed us to test the feasibility of precisely translating data from design to physical production (via the automated grammar). It also allowed us to evaluate the visual and physical aspects of the assembly system. The visual appearance and scale of the meander pattern on the corner wall proved to be very appealing. The physical aspects of the system also proved to be mostly successful. The integrated aligners in the building components held the components in place and added greatly to the stability of the corner wall. At the same time, the built-in tolerances, or gaps between components, permitted some movement of the components. This might allow structures built this way to be less prone to collapse in earthquake conditions.

The wall construction also revealed issues beyond our control. Although the individual mold layers for the wall components could be CNC-cut precisely, the thicknesses of the layers (purchased from an outside source) varied by small amounts. This, in turn, caused small discrepancies in the heights of the components. Thus, the construction of the corner wall allowed us to assess which physical parameters within our research process were controllable and which were not. The parameters we were able to control were those dictated by our program and the data used for fabrication. The variance of the material thickness was not a controllable parameter. We will have to consider finding a direct correlation between the material thickness and a tolerance variable for future development. This is an important general issue to address. In order to incorporate visually complex design patterning into an automated system for structural assemblies, a general means for fabricating complex and precise physical components directly from digital data needs to be perfected.

IV. CONCLUSIONS AND FUTURE DIRECTIONS

Our project advances theories and applications of computation and digital technologies for the design and manufacture of building assembly systems for housing or other small structures. The results of our project suggest new solutions for economical, culturally sensitive housing. Although we are too early in our research to determine exact housing costs, our process points to areas of substantial savings. A major contributing factor to cost in traditional home building is the number of steps in construction from measuring, to cutting and assembly. Our system reduces the number and complexity of steps in on-site construction by eliminating on-site measuring and cutting of components. Workers manufacture blocks from precise CNC-cut molds and assemble only.

Beyond the specific context of housing, our work has the potential to contribute to the design and manufacture of artifacts at many scales, and in domains from product design to building design, particularly for artifacts where visual aesthetics need to be considered jointly with physical or material requirements and design customization or variation is important.

Our project also contributes to the advancement of knowledge and research on generative design systems, in particular, shape grammars. The primary intent of shape grammars has been to capture and represent design knowledge on paper or on a computer screen. Our visual-physical grammars not only generate visual descriptions of designs in a language, they also generate physical and material descriptions of designs for full-scale CAD/CAM production. Visual-physical grammars provide a new, important bridge from the virtual world of design on paper or in a computer, to the physical world of design and construction.

A critical next step in this research is the generalization of strategies for defining visual-physical grammars. Vernacular or other visual pattern languages, such as the Greek meander language, can often be characterized as languages of two-dimensional, infinite "wall-paper" designs. One technique for defining a visual-physical grammar from a set of wall-paper designs is to first parse the designs into a repeating motif or motifs, and define shape rules for recombining motifs to generate pattern variations. These repeating motifs would then need to be translated into interlocking building components. For example, the motif and main repeating element of the meander shape grammar is an S-shape. This S-shape was translated successfully into interlocking meander blocks. Alternatively, wall-paper designs might be divided into simple grids of cells with embedded motifs which could then be translated into grids of interlocking blocks with imprinted motifs. These are just initial ideas.

Another important next step in our work is to expand the ease of use and accessibility of visual-physical grammars for real-world applications. The issue of accessibility is crucial for global production and proper use of our system. The automation of our visual-physical grammar as a computer program integrated technology for local computing and processor use such as 3D software and Microsoft Excel spreadsheet data. We anticipate that our system will be used in rural and developing areas so would therefore need a different platform approach. Additionally, the design of the interface, currently very simple, would require more careful consideration of the users and cultural context.

The next stage of development will be to introduce a system that is completely mobile and can be accessed from any location using a mobile internet-connected technology. This will allow us to build a more sophisticated, yet simple system that can be accessed locally or globally with the appropriate technologies. We envision having the main processes calculated and computed on a distributed server technology that can be accessed using a simple drawing interface. The output of our system will be data for assembly as simple text that can be used as Excel input (if needed), and data to be used for CNC fabrication.

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