Abstract. The promise of robotic fabrication as an enabler for mass-customization in Architecture has been hindered by the intricate workflow required to go from parametric modelling to CNC fabrication. The lack of integration between highly-specialized proprietary software, normally required to operate the machines, and most of the design tools constitutes a major limitation. One way to tackle this constraint is by developing simple tools that directly link parametric modelling to robotic coding. Accordingly, “Fisac Variations” develops an uninterrupted digital workflow from form-generation to robotic fabrication. This innovative approach to Computer Aided Design and Manufacturing was tested by studying and reengineering a specific historic construction system – Miguel Fisac’s Bones System was used as a case study – and by enabling it to address problems of contemporary architectural agenda such as flexibility, variability and mass-customization. The proposed workflow threads form-finding, structural analysis, geometric definition, CNC code generation and digital fabrication within the same open-source computational environment. In this way, this innovative procedure aims to increase design freedom while ensuring fabrication feasibility. This paper describes background research, concept, form-finding, construction process, methodology, results and conclusions.

Keywords. Parametric design; digital fabrication and construction; integrated design and fabrication; mass-customization; Miguel Fisac Bones System.
complex projects. Although numerous explorations on the robotic fabrication for architecture taking place around the world suggest promise, applications are still under development (Picon, 2010).

In many industrial settings, particularly in the automobile industry, robots have proved extremely successful for the past few decades. On the contrary, their applications in the construction industry have been slow and uneven. One of the key differences is that car manufacturing is highly repetitive and therefore robots are very finely calibrated to repeat very specific routines; calibration tasks pay back due to the high volume of production. In contrast, the construction industry requires highly customized components, especially for buildings of complex geometry, requiring a large number of specific robotic instructions. Additionally, the creation of robotic code is intricate because bringing geometric information from modelling software into the proprietary software, required to operate the machines, becomes a time-consuming and tedious operation (Bechtold, 2010).

As a response, some initiatives are starting to develop simple tools that link parametric modelling to robotic coding. This approach has been explored for robotic CNC milling by Brell-Cokcan and Braumann (Brell-Cokcan and Braumann, 2010; 2011). Project HAL, by Thibault Schwartz, develops robotic code for ABB robots directly from parametric modelling tools – McNeel Rhino/Grasshopper (Schwartz, 2009).

2. Fisac Variations

“Fisac Variations” researches the potential of directly linking parametric modelling with robotic fabrication, with the aim of engaging current architectural concerns such as complexity, variation and differentiation. The two main objectives are: developing custom code that allows for an uninterrupted digital workflow from form-generation to robotic fabrication, and testing this workflow by re-envisioning a prominent – yet rigid – construction system in contemporary key.

The digital workflow proposed by “Fisac Variations” combines form-generation, structural analysis, geometric definition, CNC code generation and robotic fabrication within the same open-source computational environment. In this way, this integrated procedure aims to increase design freedom while ensuring fabrication feasibility and stimulating design innovation.

2.1. MIGUEL FISAC’S BONES SYSTEM

As a case study, the project revisits the “Huesos Varios” (Spanish for Various Bones), developed by the eminent Spanish architect Miguel Fisac during the 60s as an elegant and efficient structural system for long span roofs (González Blanco, 2007).
The pieces that I have obtained using this architectonic-static means have resulted in sections with forms very like the bones of vertebrates. It is not that I wanted to make them like bones; it is just that they turned out that way. That makes you think that, naturally, some parallel exists. You could interpret it as proof that this is the right path; it corresponds to concepts which we see in nature.” (Fisac, 1966).

The “Bones” system consists of a string of identical concrete voussoirs that are post-tensioned to assemble long beams (Figure 1). The key point of this system is a smart and meticulous design of the cross-section, which solves several structural and construction problems: the pieces are hollow, making them lighter while keeping a high moment of inertia; the asymmetric geometry creates openings for natural lighting; the valley collects and drains the rainwater; and the curved geometry improves the acoustic performance of interior spaces. The post-tension action improves the waterproofing of concrete as it reduces the risk of cracks (Figure 2).

The major limitation of Fisac’s system lies in its inflexibility. First, the system works almost only for linear arrays of beams for flat and orthogonal slabs, which limits the building typologies that could potentially adopt this structural system. One experiment with radial array presented unresolved technical issues in relation to the joints and it was not very successful in aesthetic terms (Tejada House, Madrid, 1967). Additionally, the light wells created by the system are locked into a single pattern, homogenizing the natural light distribution and making the system difficult to accommodate different programmatic functions.

2.2. VARIATIONS

Using advanced digital tools, “Fisac Variations” expands the structural efficiency, natural light control and water draining logic of Miguel Fisac “Bones” to reach new levels of tectonic and formal complexity. The main goal is to develop a mass-customizable system that can deal with wider and more complex range of structural, programmatic and organizational requirements.
The result is a flexible construction system open to accommodate diverse programmatic functions. Moreover, the structural performance of the new typologies exceeds the beam logic and proved more efficient as they can follow natural stress lines, minimizing the bending stresses and allocating material specifically where needed.

3. Implementation

In order to attain flexibility while achieving a feasible construction method, the project integrates manufacturing constraints and robotic control into a single smart parametric model. “Fisac Variations” develops an innovative fabrication workflow for architecture by customizing open-source software for robotic fabrication. The code is based on McNeel Rhino/Grasshopper, Microsoft C# and ABB Rapid Code.

3.1. DIGITAL DESIGN: SYSTEM GENEALOGY

Fisac Variations is designed to adapt to a wide-variety of surface geometries, from flat to non-zero Gaussian curvature. The form-generation and geometrical development process takes advantage of an associative model that encodes the clever cross-sectional features of the original system into a six control points’ section (Figure 3). These variable sections can change along the span of the beams and each pair of them defines a voussoir through a loft operation. Thus, this process allows for gradual variation between pieces and specific control of its performance, being able to modulate the geometry in response to particular structural, spatial and lighting requirements.

Another innovation that the project introduces to the original system is the concept of ‘girder’, a technical improvement which enables the connection between pieces in two directions. This feature eliminates the need for continuous linear supports in the extremes – present in Fisac’s system.

The code defines a collection of beams, organized according to a quadrilateral input surface called ‘quad’. To generate the geometry, the Grasshopper definition can take two different pieces of data: a custom quadrilateral surface or four vertex points. If a custom quad surface is used as an input, the given surface is discretized
into a number of segments and corresponding fabrication curves. Alternatively, if four vertex points are used as input, an additional step allows the user to specify the geometry of the edge curves.

The script also provides detailed control of the depth and thickness of the sections, as well as the ability of determining the location and size of openings and draining channels. Structural constraints are coded to define geometric thresholds, such as the curvature that beams and girders can describe in plan. For example, in order to the voussoirs be post-tensioned, the deviation should not exceed 10% of the span.

The girders located on the edges of the quad confer the latter with the capacity to work associated with others and, therefore, to proliferate into more complex spatial and programmatic organizations (Section 6.1).

As a design output, the code creates a set of unique pieces adapted to their specific needs. The script also generates the connection between the voussoirs: a set of interlocking keys that facilitates the assembly and improves the structural performance.

3.2. ROBOTIC FABRICATION

Robotic fabrication can be applied to several tasks, including mould-making, concrete casting and vibrating, as well as voussoirs unmoulding and handling. Due to the limited scope of this research, the focus was placed on the first step of the process, mould-making, and on the development of coding that converts the geometry into robotic instructions using ABB Rapid Code. The operation sequence for cutting each piece is automatically named and stored into individualized files that feed the 6-axis robotic arm (Figure 4).
For each one-off voussoir, a customized mould is fabricated by cutting recyclable expanded polystyrene (EPS – 20kg/m³) with a hot-wire bow attached to a robotic arm. This custom tool uses standard components and a commercial AC power controller (Figure 5). As a logical limitation from this procedure, all pieces are defined by ruled surfaces.

This mould-making technique is fast, precise, affordable and easily recyclable. The tool can be adjusted depending on the desired size of the piece to be cut; yet, the cutting speed needs to be calibrated according to the length of the wire. A complete cutting sequence of a full-scaled beam module takes approximately 15 minutes while a girder module takes 25 minutes, for pieces one-meter long.

4. Tectonics: Concrete Casting and Off-Site/On-Site Assembly

The EPS moulds are then casted with concrete to produce the highly-customized voussoirs. During the 60’s, when Miguel Fisac developed his 'Bones', the minimum thickness and the maximum size of the voussoirs was limited by the concrete performance and the vibration techniques available at the time. Today, high-tension and self-compacting concrete mixtures combined with efficient assembly lines facilitate the process and open a new spectrum of sizes and thicknesses. Also, departing from the original system, the pieces are not hollow: after the casting, the core is left to fill the cavity as an insulation improvement, taking advantage of the EPS thermal properties (Figure 6).
Regarding the assembly sequence, first all the voussoirs corresponding to a beam are interlocked on the ground using the EPS mould as a support. Secondly, they are post-tensioned to assemble each beam individually. This process can be done either off-site or on-site. Finally, after putting all the beams in their final position – with or without the use of scaffolding depending on the support condition-, the girders are post-tensioned in the opposite direction, perpendicular to the beams connection.

5. System Performance

The resulting system introduces variability in both the overall and the module geometry. As a result, “Fisac Variation” is able to adapt to a wide range of span-lengths and structural typologies, from flat slabs to compression-only structures and to free-form surfaces. This condition provides the project with a new expressive quality and flexibility to adapt to topological variation and functional complexity. Accordingly, the movement of the six points that determine the encoded cross-section produces differentiated beams, allowing customization of the interior space morphology as well as fine-tuned control over acoustics, water drainage and natural lighting (Figure 7).

The sound performance can be enhanced by smoothing the beam surfaces, reducing the noise reflection within the building. Regarding the rain water, it can be canalized into desired drainage paths through the subtle movement of the lips that form the upper surface of the pieces. The same feature also permits to adjust the light entrance, admitting gradual or abrupt variations, in harmony with spaces use and distribution.

Figure 6. Full-scale voussoirs – wirecutted EPS (left) and casted concrete (right).

Figure 7. Structural performance (left), direct and indirect natural lighting (centre) and water drainage strategies (right).
6. Design Speculations

6.1. PROLIFERATION

Fisac Variations, as building system, can achieve complex organizations through the proliferation of quads into larger fields. This property incorporates new layers of sophistication to the research project and expands its range of application by the capacity of allocating contemporary mixed-use programs into complex spatial configurations (Figure 8).

6.2. SCALES OF APPLICATION

Because of the discretization principle under which the geometry is conceived, explained in detail in Section 3.1, the same quad can be subdivided into different number of voussoir. By augmenting their quantity, the geometrical resolution gets higher, enhancing a detailed control over the system performance described in Section 5. Nonetheless, the pieces become smaller, increasing fabrication and assembly complexity. As a consequence, the final number of modules is a negotiation between these two factors. In a speculative perspective, possible applications of the proposed system can range from domestic to infrastructural applications (Figure 9).

7. Prototypes

Several building prototypes and consultancy with engineers showed initial feasibility for “Fisac Variations” as an efficient customizable structural system and
established accurate thresholds for spans and geometrical variation. As a proof of concept, a 1:5 large-scale structure in EPS was built, satisfactorily testing geometric accuracy and post-tension feasibility, as well as aesthetic and spatial effects (Figure 10). A full-scale mould was cast and proved operative.

8. Future Research

Several areas of research deserve further development in order to make the proposed workflow and building system fully operational. First, integrating a structural analysis component is essential for tectonic reasons and will also enrich the design process. Second, increasing the scale of fabrication will require additional research on larger robotic shops and customized CNC wire machines. This feature would allow exploring new ranges of robotic fabrication as described in Section 3.2. Finally, on-site assembly sequence, which includes transportation, placement and scaffolding, is on its initial stages of developments and demands careful study.

9. Conclusions

“Fisac Variations” researches the potential of robotic fabrication and integrated design-to-fabrication workflows as a means to enable complex geometric and tectonic assemblies, which rely on mass-customized components. Results presented in this paper show how customized scripts can embed fabrication constraints to parametric modelling and thus simplify the complicated workflow that currently limits robotic construction in Architecture.

As a specific project, “Fisac Variations” proposes a new efficient, adaptable and feasible structural system, attainable only through integrated use of digital design and fabrication. The result expands the range of possible uses of the original Bones System and helps to overcome some of the formal and structural limitations that caused its obsolescence. As with the case of Miguel Fisac’s designs, the formal and expressive qualities of the resulting models and prototypes reveal that the system can drive structural efficiency into sophisticated architectural spaces.
Instrumentally, the highly customizable set of tools and workflows developed through this project complements ongoing robotic coding research and is open to be applied over different tectonic systems (Brell-Cokcan and Braumann, 2010). On a broader outlook, this investigation contributes to current efforts of Computer Aided Design and Manufacturing to realize complex one-off projects.

Endnotes

1. Several projects of EPS cutting with a hot-wire cutter bow attached to a robotic arm have been developed during the last few years at the University of Michigan Taubman College of Architecture and Urban Planning Digital FABLab, directed by Wesley McGee.

2. Changing the length of the bow also modifies the length of the hot-wire; therefore, the cable resistance is different in each case, affecting the amount of power needed to cut the EPS. In any case, the speed needs to be calibrated to avoid geometrical imprecisions while cutting the mould: if the speed is set up too fast, it would drag the wire; if the wire runs too slow, it would melt the foam excessively.

3. While off-site assembly offers better performance according to building time execution, on-site assembly overcomes the existence of transportation constraints, typical of crowded urban centres—sometimes with narrow streets—by moving the voussoirs to the site one by one.

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