

Digital Construction

Automated design and construction experiments using customised on-site digital devices

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Abstract. *This paper presents a currently on-going research trajectory, investigating integrated design and build work-flows using generative design strategies and custom built fabrication devices. The aim of the research, which is being developed through a series of experiments and workshops, is to explore scenarios in which these work-flows can produce emergent architectural structures which are highly adapted towards the intended performance within their specific context and site. The research has produced a number of installations and prototypical structures which test the practical and theoretical dimensions of the methodology explored. This paper will introduce intriguing new scenarios in which the architects' role is focused on an indirect, advanced level of control of the process of design, allowing for a more open-ended method of negotiation between structure, users and environment*

Keywords. *Generative design; digital fabrication; customised CNC devices; digital on-site construction.*

INTRODUCTION

This paper will describe academic research and teaching experimentation that has attempted to set up automated design and construction workflows using generative digital design tools connected to on-site digital fabrication devices. This paper will show how relatively simple experimental set-ups using customised CNC or Arduino-based devices offer a low-cost alternative to the on-going trend of using robotics in architectural academia and practice. Technologies such as CNC cutting and milling are being used to explore design concepts through scaled models as well as for the manufacturing of 1:1 building components, allowing the incorporation of fabrication constraints into design processes to construct projects of ever increasing digital complexity.

CONTEXT

Digital design and manufacturing technologies have given architecture the means to explore new architectural languages and fabricate structures with corresponding complexity, yet this research is aimed beyond simply pragmatic goals based in the realisation of geometrically complex projects using fabrication equipment borrowed from other industries.

This paper investigates how the changing nature of design processes linked to digital production might impact the conception and materialisation of architectural projects of a much greater range, developing relatively simple fabrication devices that are custom designed for each specific architectural goal. Similar to how scripting has allowed designers

to customize and hijack what were simple general CAD packages for drafting, custom fabrication devices are allowing for the exploration of many new ways of integrating digital and physical realms.

An example of this integration is the RepRap project by Dr Adrian Bowyer which is based on an open-source, low cost 3D printer that can self-replicate. The project makes possible the democratisation of manufacturing small consumer products as part of a community of users and designers that form large networks of on-going improvement and exchange. The work presented here investigates similar technologies that operate at an architectural scale. It explores how design and build processes can be set up around these technologies that explore architecture can be produced out of a process that is integrated within its context.

Viewed within a framework described by Sanford Kwinter as '*shifted from classical mechanism and reductionism to a biological model*' (Kwinter, 1993), it considers buildings to be part of a larger ecology that incorporate communities of users, technologies and materials, and other performance criteria that shape space. The projects presented here explore new scenarios for the creation of architectural structures, experimenting with mobile and low-cost fabrication devices, programmed with generative design algorithms which are directly driven by sensory technologies.

SCRIPTING ARCHITECTURAL DESIGN

The linking of digital and physical construction principles requires the conception of rule-based design methods that can produce a range of different outcomes within the limitations of the chosen systems for fabrication and construction.

As Dr. Mark Burry and many others have pointed out, this 'parametric thinking' is not a particularly recent phenomenon and can be recognised in gothic cathedrals or in the work of Antonio Gaudí. Yet digital methodologies allow for generative models with a much more direct and rapid feedback loop between evaluation and design, incorporating development and evolution of design proposals into a

process that mimics growth and adaptation of structures within the parameters of limited resources, competition and environmental pressures.

As Michael Weinstock writes, the abstraction of principles from the way in which biological processes develops a natural material system can be highly instrumental in the conception of architectural processes which operate within artificial contexts (Weinstock, 2010). Weinstock observed that natural material systems are often rule-based and use principles of organisation which integrate structure, material and form.

In his seminal publication '*An Evolutionary Architecture*', John Frazer demonstrates the effectiveness of generative design processes in which the aims and evaluation criteria are clearly defined. In evolutionary design processes aimed at growing optimised structures it is important to understand the interactions between the several agents that are involved, using feedback mechanisms to guide adaptation (Frazer, 1995).

SCRIPTING MATERIAL FORMATION

The integration between scripting, materials and fabrication technologies is crucial to conceive effective generative systems, as exemplified in the work of Eladio Dieste who developed a celebrated body of work out of the coherent structuring of bricks into extraordinary structural and spatial performances, developing design ideas '*not out of an abstract, geometric application, but out of an idea of construction*' (Escolano, 1998, on Dieste). His influence can be traced through to the work of Gramazio and Kohler, with some of their most iconic projects built out of digitally programmed bricks.

Gramazio and Kohler's design explorations are based on the sequential layering of material, which is directly analogous to the sequential looping of their digital design process. They write that '*when architecture becomes the design of material processes, we no longer have a static plan in front of us, but a dynamic set of rules. We design a behavior*'. (Gramazio and Kohler, 2008), suggesting that the choreography of the production process based on machine

anatomy and movements is an important driver of design.

NEW SCENARIOS OF DESIGN

The inclusion of concepts of behaviour might imply that more autonomy can be delegated to design and build machines, and instead of programming fabrication sequences they might be equipped with sensory and decision making abilities, allowing them to become intelligent partners in the process. After the Architecture Machine Group was launched at MIT in 1968, Nicholas Negroponte wrote that *'in most cases the architect is an unnecessary and cumbersome (and even detrimental) middleman between individual and the built environment'*, stating that an ideal scenario would be *'a physical environment with the ability to design itself, to be knowledgeable, and to have an autogenic existence'* (Negroponte, 1975).

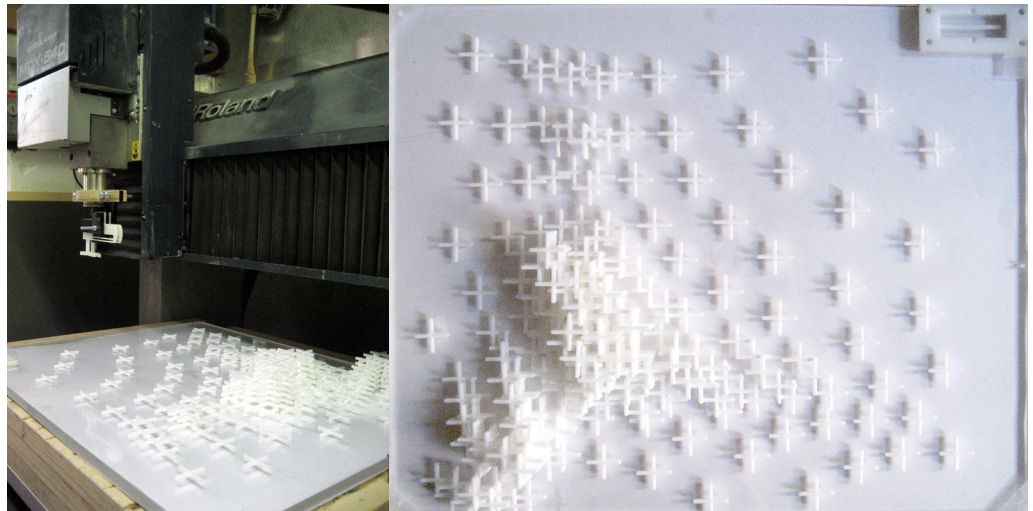
Our research is related to this ambition, but with the acknowledgment that there must be a conscious creation of a programmed system of rules, material systems and fabrication machine behaviours, to allow for a certain amount of flexibility in implementation while at the same time safeguarding certain

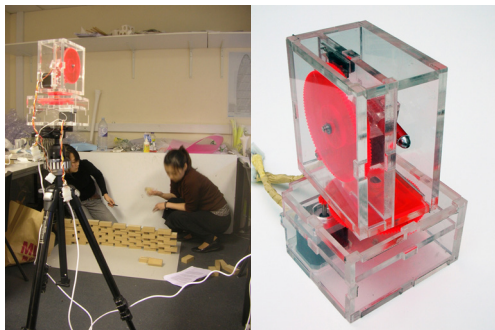
intentional qualities of performance by the structures resulting from the process. This 'programming of the system' is where the architect design responsibilities and the search for opportunities will be concentrated, developing and testing genetic codes and implementation scenarios which allow for an open-endedness to incorporate unpredictable requirements raised by users, context and site.

METHODOLOGIES FOR EXPERIMENTATION

Starting with introductory tutorials and exercises focusing on the design and fabrication of interactive hardware set-ups, each course asked students to propose innovative and integrated scenarios for an overall design and make process. This approach typically included the conception of design algorithms and the scripting of fabrication device instructions, connected to a specific material system that has been developed in parallel. A particular geometrical system would serve as a common language between fabrication devices and design scripts, however in a generative and open-ended manner, leaving the final outcomes to emerge out of the process.

Figure 1 and 2
'Spacers' project testing a
'hacked' CNC machine and
cluster formation.





INCREMENTAL DEVELOPMENT OF DESIGN AND FABRICATION SYSTEMS: EARLY EXPERIMENTATION

The first test was titled 'Spacers', and was based on the 'hacking' of a small sized CNC milling machine to turn it from a subtractive to an additive device, making it pick and place 3mm tile spacers in an emergent pattern that visualised how a starting grid with varying spacing can result in stacked formations with varying densities and height. The test proved the possibility of creating simple custom designed fabrication hardware and custom generated G-code, to choreograph machine movements based on simple stacking rules (figure 1 and 2).

The second project is investigating the potential of custom-built CNC devices, using a stepper motor controller set and Rhino scripting. The project titled 'Ginger' (figures 3 and 4) was inspired by Gramazio and Kohler's work but proposed a low-cost device that incorporated a laser pointer to translate design information into the construction site of a programmed brick wall. Human building operations were integrated in the machinic process, using each of the components in the system for the tasks for which they were best equipped.

The project demonstrated a successful workflow from design to production and speculated on the advantages of small custom devices over existing industrial machines, such as mobile applications and scalable working area.

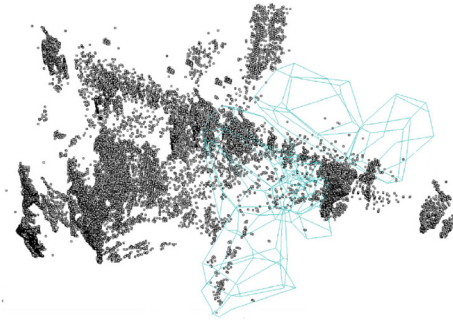
Figure 3 and 4
'Ginger' CNC laser pointer device using a 2-axis rotation mechanism and human assistance for building programmed brick walls.

The projects presented here are part of on-going programs for architectural education, organised as part of master-level courses or as independent workshops open to students and practitioners with various levels of expertise. Connected to the research agendas of the tutors involved, they were developed by students and staff around previously prepared hardware and software protocols, including stepper motor control technology and Arduino micro-controllers. Tracing the development of several different processes and techniques, the projects described are all organised toward a common goal which is a complete working model of an automated digital design and construction process, investigating the topics as described above.



Figure 5 and 6
'Otto-Mater' project using a SERB robot to scan and instruct alterations to a gradually developing light filter.

Figure 7 and 8
'G-Cloud' project developed from 3D scans of people movement through the site, materialised in a timber structure built with help of a CNC pointing device.



A third series of projects introduced Arduino micro-controllers in a workshop aimed at exploring mobile robotic fabrication devices equipped with sensors and simple behavioural rules. One of the projects titled 'Otto-Mater' combined the open-source SERB robot design with an environment in which a Lycra ceiling surface was being manipulated (figures 5 and 6). The robot used several behavioural routines to scan the environment and indicate to the human collaborators where to place weights or wires to introduce pulling points onto the fabric. The structures that emerged over time were acting as light filtering structures, amplifying and visualising the lighting conditions that were initially imposed.

Testing Integrated Design and Fabrication Systems A fourth project titled 'G-Cloud' used the opportunity to build a large scale structure within a forest setting to test a first combination of most of the aspects developed in the projects describe above (figures 7 and 8). The project evolved around of a scenario which includes an aggregate material system with simple connections, and a digital workflow which translated 3D scanned site information on people movements and densities towards a corresponding triangulated cellular structure which traced and articulated the boundaries of the movements. Higher frequencies of movement were translated into increased densities within the structure, visualising previously invisible qualities on site and guiding subsequent visitor movements along specific paths.



INCREMENTAL DEVELOPMENT OF DESIGN AND FABRICATION SYSTEMS: ON-SITE SCANNING, DESIGN GENERATION AND CONSTRUCTION

An experimental project titled 'G-Cloud' was set up as part of a workshop project aimed at integrating the sequential fabrication and evaluation of structures within process of design decision making itself. The project explored the possibilities for an automated scan/design/build strategy, using newly available 3D scanning equipment and design algorithms in combination with a low-tech construction method that uses human participants and instructions from digital devices. It was organised at a forest location, allowing for the use of local trees to attach digital hardware and offering construction materials in the form of locally harvested timber strips.

The scanning and design generation workflow that was used, centred around the X-box Kinect 3D camera and a series of algorithmic procedures, to process the received scanning data into simplified point-cloud descriptions and translate these into corresponding triangulated grid definitions that could be constructed as a structural frame. By capturing sequences of people positions in the site, a three-dimensional mapping of movements across the site was reconstructed, indicating areas of higher and lower frequency of movements over time. Areas with higher intensities of movement over time were designated as void spaces, around which

a triangulated structure was generated with corresponding densities. Using an algorithm based on a simple cell-packing principle, a self-structuring spatial frame was generated which would be in structural equilibrium during each phase of construction [Figure 7].

The triangulated structure in the design software was described as a series of coordinates in 3D space, which were indicated on site at 1:1 scale using a custom-built CNC positioning device. This device worked through varying the length of three wires that were fed through pulleys connected to the trees, moving a pointer to a specific coordinate and then pausing to allow the workshop participants to measure, cut and attach new members onto the structure [Figure 8]. The node details were designed to be easily constructed using hand tools. Laptop computers on site were used to keep track of the number of connections built, with a node numbering system to indicate to the builders which points to connect. A sawing station was set up to cut timber strips (with a section of 25x25mm) to size, with participants developing a fast manufacturing and assembly workflow as their experience with the project set-up increased.

The 'G-Cloud' project demonstrates a successful fabrication process, based on an integrated construction workflow using an on-site positioning device and an easy to assemble material system implemented by humans following machinic instruc-

tions. The elimination of the need for the prefabrication of large numbers of mass-customised elements decreased preparation time and increased construction speed. It also allowed for easy adjustment to imprecisions in the construction caused by uneven terrain and human error, due to the calibration of the indicating device to a global coordinate system and the sequential construction process.

The project also shows an alternative conceptual design approach that is in contrast with current linear processes that are based on file-to-factory methods and where rationalisation and implementation operate independently and after the process of spatial design. The work employs high-tech software applications and mobile hardware to enable deployment in relatively low-tech environments and locations, using locally available resources for designs that are adapted to local contexts and climate. The design intent embedded in translation algorithms that process scanning data into design, guarantees structures to fulfil performance criteria while allowing the outcomes to be unpredictable yet highly adapted to its purpose and site.

CONTINUOUS ON-SITE SCANNING, DESIGN GENERATION AND CONSTRUCTION

The second project developed during MakeLab was titled 'Blue', which used a similar CNC wire pointer device as described before but in this case con-

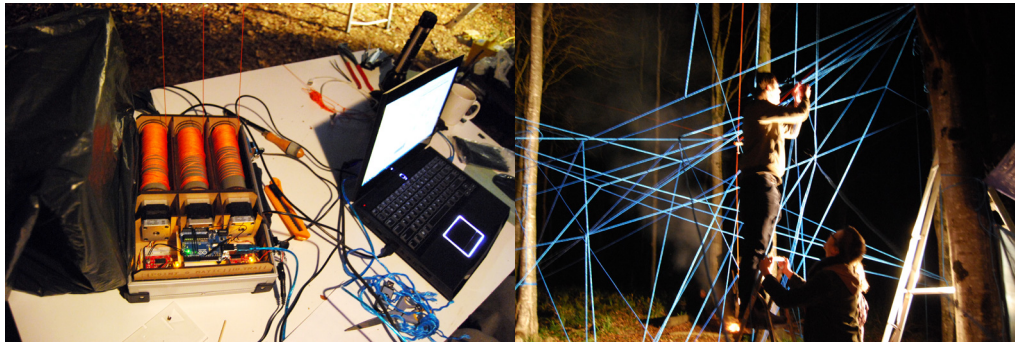


Figure 9 and 10
Wire structure produced
through an on-going process
of scanning, generative design
and construction within the
site.

Figure 11
Wire structure produced
through an on-going process
of scanning, generative design
and construction within the
site.



nected to a dynamic digital design model which was continuously monitoring colours and light values in the site. The system was set up using an Microsoft Xbox Kinect 3D camera, which produces a true three-dimensional data model of objects and their colours within its scanning area. The project started with the scanning of a person moving through and inhabiting the site, to determine a central area around which an enclosure built out of blue rope would be gradually constructed.

This project focused in particular on how to drive a slightly more complex material system, applied in a three-dimensional space, through simple rules. The project also relied on the collaboration between devices and participants, but with the digital installation set up as an active partner in the construction, continuously scanning for previously built rope and indicating new points to attach additional wires and connect them to the surrounding trees or

terrain. The digital system would work in a similar way to how a spider weaves its webbing, following a sequential and layered series of movement patterns which produces the final physical structure.

The experiment achieved a continuous and on-going feedback loop between sensing, design generation, construction and evaluation. The use of the Kinect and an improved wire pointing device which sent or received data in real-time through Rhino/Grasshopper made it possible to monitor the output structure as it was being built, and evaluate its performance in its real environment and context (figures 9,10, 11). During this process the design instructions were being adjusted based on the monitoring, allowing the structure to evolve over time into an unpredictable final formation yet achieving predetermined goals.

The performance criteria for the structure, which was also built in a forest clearing in between several

trees, were to enclose a given space (based on scans of people standing and interacting in the site) and try and block sunlight entering this space. Additional rules such as the ability to sense previously built material allowed the system to keep adding structure following specific geometrical patterns, allowing people to install a growing wire network which was fully in tension. The resulting structure shows various levels of porosity based on the orientation of it towards the light, and shows how simple scripted procedural logics can result in a complex layered and subdivided structure that produces emergent qualities within the site.

CONCLUSIONS

The research presented in this paper explores the opportunities found within the integration of sensors, material systems and fabrication devices into generative on-site design and construction strategies. It has shown how the monitoring a set of properties can drive consequential design adjustments that can be implemented right away, adapting the final outcomes towards the intended functionalities. By creating feedback loops between environmental sensory inputs and construction implementation, it is possible to explore strategies for fabrication where the final construction is not predetermined, but instead is producing emergent qualities based on performance-based rules.

The key potentials of this approach may be: architectural structures can be produced on site, with specifically adapted geometrical and material organisations. Buildings can be better equipped to perform within their context, with integrated functionalities and environment-specific, performance-based implementation of designed rule-sets and procedures. Architects may engage new types of projects and achieve solutions for areas and programs that are currently not yet addressed. The increased control over production and possibility for user participation offers a democratisation of design decision making and facilitates negotiation between large participant groups. The role of the architect using these methodologies may shift from controlling

the end result to designing a process-based, quality driven generative method, allowing successful methodologies to be implemented towards a range of programs and sites. The research may increasingly incorporate intelligent behaviours, mimicking processes of self-organisation as observed within nature. Providing an alternative vision to static and idealised architectural solutions, these methodologies are based on the unpredictable and dynamic processes that inform real-world architectural challenges and briefs.

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