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RUAIRI GLYNN & BOB SHEIL

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FABRICATE: MAKING DIGITAL ARCHITECTURE

RUAIRI GLYNN & BOB SHEIL

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We wish to make a special thanks to Marilena Skavara, who has tirelessly assisted us in organising FABRICATE 2011's conference, publication and exhibition.

Ruairi Glynn and Bob Sheil

INTRODUCTION

ACADEMIC

INTRODUCTION

FOREWORD ROBERT AISH

DIRECTOR OF SOFTWARE DEVELOPMENT,
AUTODESK PLATFORM SOLUTIONS

FABRICATE: Making Digital Architecture gathers together a unique selection of research and exploratory prototypes and records the creative thinking of innovative designers and researchers. Fabrication depends on the ability of the designer to harness the properties of materials and to anticipate how these can be transformed by the sequencing of manufacturing operations. It is not just the fabrication processes described here that are important but also how these relate to, or express, design intent.

Behind many of these examples lies the creative use of design computation tools. Again, it is not just the computation tools that are important but how these relate to or express design intent and can be used as an intermediary between the designer and the fabrication process. Are these computation tools primarily focused on creating computational analogues of tangible aspects of design, or on abstractions? Such abstractions might be conditional, dependency, repetition, iteration, recursion, convergence, encapsulation and inheritance. How do these abstractions intersect with concepts used in contemporary design thinking such as commonality, variation, differentiation, adaptation and emergence?

Essentially we have a network of connections between design (intent), computation (abstraction), fabrication (realisation), the resulting building (as artefact) and the building user (and their 'user experience'). Here we see 'fabrication' as an important component within a larger system. Both fabrication processes and design computation can be viewed as important design tools. What is the relationship between tools and design? Tools provide possibilities, from these possibilities we discover advantages, advantages become a convenience, and convenience can too easily become a convention. There are alternatives: rather than supporting just the more efficient execution of conventional tasks, tools can encourage new ways of thinking. The creative use of a tool should include opportunities for the designer to embed his own design logic within that tool. Such customisation should be recognised as a key aspect of design creativity. A creative tool is one that facilitates this customisation and can be used beyond what was envisaged by the original tool builder. Tools, therefore, embody conceptual knowledge. Harnessing tools may relieve the designer of some physical and mental effort but also require the acquisition of this conceptual knowledge. Never be limited by the available tools. Think beyond the tool. Tools should challenge the designer. The designer should challenge the tools. Become you own tool builder. Challenge yourself.

When you read the different sections of this book, I would like to encourage you to ask a number of critical questions. Is the design intent explicitly stated? Or, by reading the text and reviewing the images, is it possible to recover some sense of what this design intent might be? What was the relationship between the fabrication process and this design intent? Was the intent to explore a particular material or fabrication process (which, at a research or 'proto-architecture' level of inquiry, is quite legitimate) or was fabrication being used to realise some broader design intent? What computing was used? Was this computing primarily focused on a digital representation of the 'tangible' (geometric form, material properties and manufacturing operations)? Or were additional computational abstractions used and how did these contribute to the design process or design outcome? What additional concepts, insights or possibilities did the designer acquire through the use of these abstractions? And (to rephrase the previous questions) what was the relationship between the computational abstraction and design intent? Was the intent to explore the abstraction (which, at a research 'proto-architecture' level of inquiry, is quite legitimate), or was the abstraction being used to realise some broader design intent?

The progress of architectural practice can be characterised by two opposing forces: a convergent force driven by the spirit of the times and a drive for innovation. Common themes and interests emerge from the cultural milieu, which seem to act as 'attractors' for the field of practice and contemporary fashion. One could imagine this in terms of a flocking algorithm, in which individual birds move towards the heart of the flock; this dynamic giving rise to the identity of the flock – the similarities between the paths of the individuals which lead it to cluster and cohere as a discernable object – and the trajectory of the whole flock over time.

Opposing this is a drive for innovation. Innovators aim to distinguish their practice from that of others and current fashions. They continually strive to fly away from the flock, and where it has been in the past, to explore new territory. However, by trying to get away from the flock the innovators merely help determine its direction of flight. They become the moving front edge of the flock. From time to time different groups of innovators choose to explore different trajectories and the flock may divide, often only to come together again some time later.

The spirit of the times is often summed up by an 'aesthetic' – the formal and material properties of buildings that are most easily seen and emulated. However, underlying these surface details are at least three sets of concerns by which practices seek to identify themselves and to distinguish themselves from others: an ethical position (an attitude towards sustainability, for example); a spatial practice (often an approach to the spatialisation of the social) and a working process (the methods through which the practice pursues its design).

Of course, from an individual's point of view inside a flock it can be hard to see its shape, even to see that you are part of a flock at all. The role of the critic, the curator and the conference organiser is to give shape to the flock – to help create the cultural milieu by defining and reflecting back on the individual the dynamic of the group as a whole; to help make sense of the apparently random and divergent paths of individuals seen close up. This is the role of this conference and book.

Here our focus is primarily on 'working process' – the processes in design and fabrication by which material components are shaped and brought together to produce spatial and formal objects. The effects of computing on architecture are far reaching. They bring the ability to control fabrication digitally, to drive cutting, bending and assembly; to simulate and optimise material performance, to control geometry with precision. They bring the potential to put the designer once again in direct control of the craft of material shaping and construction, something unseen since the medieval craftsman masterbuilder gave way to the divisions of labour – and the constraints of symbolic representation of the production drawing – that characterise the modern industry. The fast-moving front edge of the flock is an exciting place to be.

FOREWORD ALAN PENN

PROFESSOR OF ARCHITECTURAL & URBAN COMPUTING,
DEAN OF THE BARTLETT FACULTY OF THE BUILT ENVIRONMENT, UCL

ACKNOWLEDGEMENTS RUAIRI GLYNN & BOB SHEIL

FABRICATE: Making Digital Architecture is a selection of articles by designers, engineers and makers within architecture, construction, engineering, manufacturing and computation. It is published alongside FABRICATE 2011, an internationally peer-reviewed conference held at The Bartlett School of Architecture, University College London, from 15–16 April 2011, for which over 240 submissions were received from 31 countries, including 35 higher education institutions and 28 international consultancy firms. We are immensely grateful to all who submitted and also to our panel of 18 advisors and reviewers for their council, patience and time.

The works presented here are from leading consultancies such as Foster + Partners, Zaha Hadid Architects, Arup, Buro Happold, Amanda Levete Architects and Ron Arad Associates, and from renowned institutions such as Delft, Harvard, MIT, The Bartlett, CITA and the AA. Projects cover a broad cross-section of scales and typologies of contemporary architectural and engineering innovation, including recently completed buildings, new works in progress and the latest research in design and digital manufacturing. Together these works encompass much of the breath, complexity and new skills required in making architecture with digital tools and techniques. Punctuating the chapters on Academic- and Practice-based research, our invited keynotes to FABRICATE 2011 – Mark Burry, Philip Beesley, Gramzio & Kohler and Neri Oxman share their thoughts with esteemed experts, Mark West, Michael Stacey, Hanif Kara and Sean Hanna.

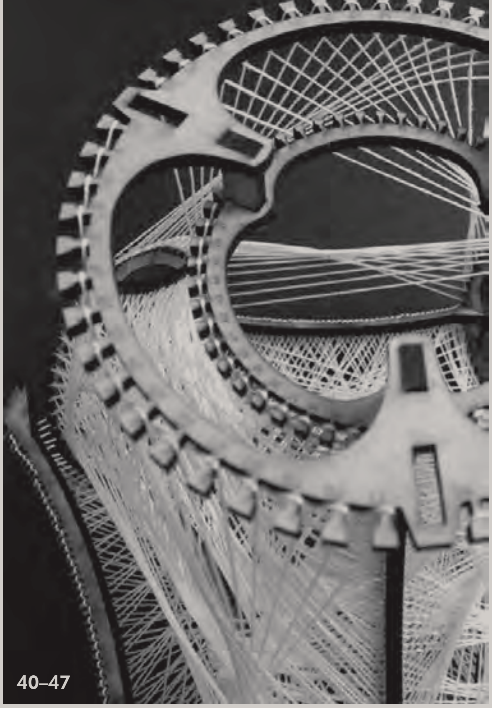
FABRICATE 2011 was planned to follow the 'Digital Architecture London' Conference and 'Digital Hinterlands' exhibition organised by The Bartlett UCL in September 2009, and the associated publication *Digital Architecture: Passages Through Hinterlands*, edited by Ruairi Glynn and Sara Shafiei. FABRICATE is also in some way a response to the highly successful 'Fabrication' Conference held in Waterloo in 2004, organised by the Association for Computer Aided Design in Architecture (ACADIA). We thank its Chair, Philip Beesley who has been a constant support.

Now, some six years later, the novel technologies and techniques discussed then are becoming commonplace in academic institutions and a growing breed of young architect-fabricators are challenging conventional modes of practice, relocating design to a position where material knowledge is both tacitly understood and fully exploited. We believe that the work presented here demonstrates many of the opportunities fabrication technologies offer the designer for greater control, ownership and influence over the processes by which our built environment is generated and regenerated.

It was by pure chance that both this publication and the associated event represent work from practice and academia in equal measure. Too much could be read into such an outcome but, at the very least, it reveals that our invitation to explore FABRICATE as a theme has attracted significant and broad interest across the key threshold, where innovation, vision, feasibility and collaboration meet. As the scope and diversity of work shown here very clearly conveys, new protocols of engagement between the design and making of digital architecture offer disciplines on all sides the challenge to rethink fabrication as a design activity, and to rethink how the necessary expertise to master this field can be acquired.

We owe thanks to a large number of friends and colleagues. Firstly, to The Bartlett Architecture Research Fund for its vital support at the very early stages of planning, to our partners, The Building Centre, for their support and advice, to Dezeen for their promotional efforts, and to Autodesk for their generous support towards the book. Amongst a large group of generous and supportive colleagues, we particularly wish to thank Professors Alan Penn, Jane Rendell and Stephen Gage, for their valued council and guidance, and Dr Marcos Cruz for his support and cooperation. For our striking conference identity, meticulous publication design and her patience, our thanks to Emily Chicken. We are indebted to our esteemed group of peer reviewers and panel chairs onto whom we transferred a workload more than twice the agreed quantity, and whose extensive, professional and thorough response, the quality of this endeavour rests upon. And last but certainly not least, to our present and former students whose appetite, verve and enthusiasm for ambitious experimentation continues to urge us on.

ACADEMIC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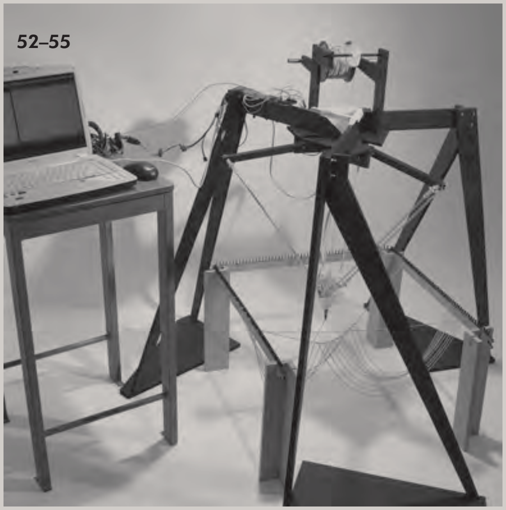
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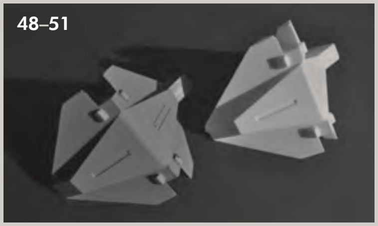
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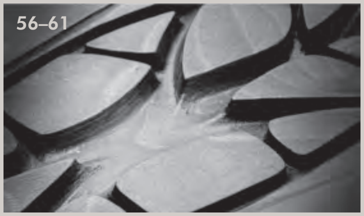
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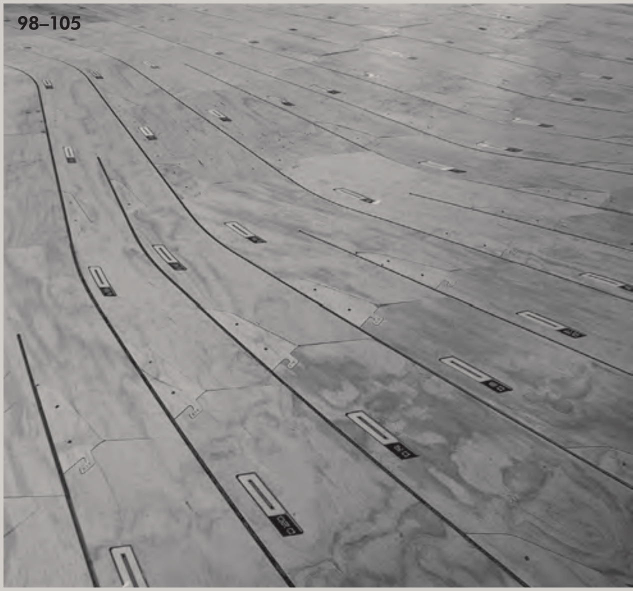
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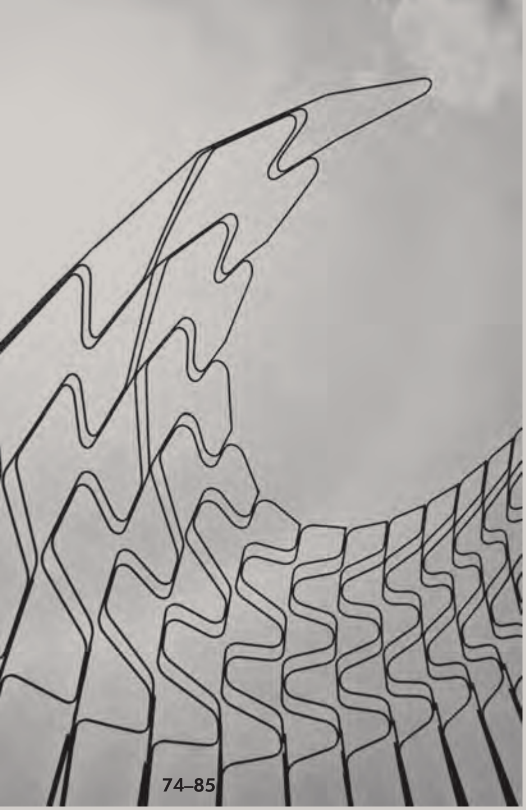
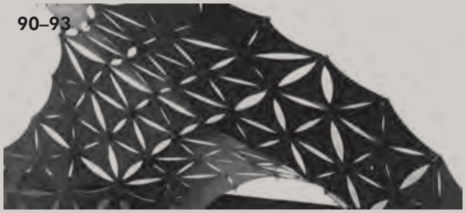




ACADEMIC CONTENTS

In dividing architectural research between practice-based and academic classifications we raise a dichotomy typical of but problematic to the discipline. Distinctions made between architect, programmer and structural, mechanical and material engineer are equally problematic. Produced by teams of multidisciplinary practitioners this publication scrutinises the demarcation of roles in the construction industry, particularly that of the architect, suggesting alternative models of design through to production. In this section we witness how schools of architecture are leading and responding to changes in our discipline brought about by the accelerating adoption of digital fabrication technologies. Case studies come from multi-institutional programmes, departmental research groups, doctoral candidates, design units and individual graduates. Much of it is proto-architectural in its realisation, exploring the performative capabilities and spatial qualities of material systems. The methods and experiences shared clearly demonstrate that the process of design to production is not as linear and reductive as some 'file-to-factory' evangelists might suggest. Feedback systems rich in iterative physical testing, coupled with parametric modelling tools, are pervasive in the work. Material intelligence, manufacturing constraints and assembly logics are key parameters in this new design space. Matter, rather than being inert, is appreciated and interrogated for its responsiveness. Early physical testing of assemblies drive digital models and decision making, countering a common critique of digital architecture's bias towards form before material.

We begin with case studies investigating the design and fabrication of complex geometries that bridge the widely recognised gap between the generation and materialisation of digital form. Menges, Schleicher & Fleischmann's Research Pavilion at the University of Stuttgart presents one strategy of material-oriented computational design where structure and space is informed by the physical behaviour of bent plywood and the constraints of their fabrication tools. The pliability of this material is further utilised at the Centre for Information Technology and Architecture, Copenhagen, to build 'soft' responsive environments. Coupled with servo motor actuation and a secondary pleated manifold it suggests that material understanding could inform the actuation of kinetic textile structures to work intelligently with changing physical load-paths. Through continual interaction between embedded micro-processing and material computation, environments saturated with sensing and actuation forge hybrid digital/analogue networks. ProtoNODE, presented by the Hyperbody Research Group, Delft, probe possible human-human, human-object and object-object relationships enabled by a responsive modular assembly. Just how small we conceive of these networks, and the potential they have not just to think but also to construct and repair themselves, is provocatively examined by Skylar Tibbits' system of mechanical logic modules for self-guided-assembly.

Where architects may conventionally turn to other disciplines *(namely engineering)* to solve problems associated with constructing complex form, a number of featured research projects are utilising robotic manufacturing techniques spearheaded by the automotive and aeronautical industries. Built works by the University of Michigan Taubman College and ETH Zurich demonstrate the latent potential for novel solutions and new opportunities to be found within generic robotic armatures. With CAD/CAM facilities now commonplace in architecture schools and open-source initiatives such as Fab@Home and RepRap gaining recognition, it is not surprising that designers are looking beyond existing fabrication technologies. A generation of confident, computationally trained and materially literate students from The Bartlett School of Architecture, Architectural Association and the Institute for Advanced Architecture of Catalonia present hacking, reformatting and reinventing fabrication processes to stimulate new building scenarios, site- and material-specific tools. The range of 'off the shelf' and custom machinery employed, and the techniques invented throughout this publication are remarkable, but few of its authors attribute much value to the machine itself but rather to the opportunities they present. There is a common humility in their endeavours, skipping over their intimate knowledge of servo control, communication protocols and tooling parts as casually as preceding generations talked about their parallel rule or set square.

In bringing together the themes of the conference and publication it was important that, along with exploring the opportunities for innovative design, we would demonstrate how architects are offering solutions to two of the most pressing economic and sustainable issues of our time: the shortage of energy and the need to reduce carbon emissions. These designer-makers, developing their own tools, handling materials and observing fabrication in action, are acutely aware of the off-cuts, the fumes, the weight and issues of assembling their work. Efficiency and environmental impact are never far from their mind, waste is considered alongside the intended artefact. Such sensitivity is widely missing in a profession that has for so long seen the pursuit of intellectual labour as superior to that of physical labour.

From the fifteenth century to today, architects have increasingly made drawings and models, not buildings. The dominant feature of the architectural drawing's role in representing the visual before questions of material and construction is later elaborated. It is uncommon to see an architect, particularly in practice, using the drawing for its potential to act as an analogue, allowing instead for techniques and medium to infer methods of construction, material and meaning. The process and tools of representation are called into question and recalibrated by Nat Chard through an account of a series of his built drawing instruments, which operate between drawing and making, indeterminacy and precision. Enabling unpredictable deviation to be celebrated when fortuitous, tempered when necessary and fundamentally harnessed, Phil Ayres presents feedback systems between virtual models and physical prototypes as a response to his critique of predictive modelling. The imperfect transformations back and forth between digital and physical artefacts are, from one perspective, an engineering problem to be solved but, from the perspectives of a number of projects here, serendipitous and productive opportunities. Flourishing in the 'noise', Shaw and Trossell present a series of case studies ranging from the analytical to the speculative, revealing surprising new design strategies formed through their experimentation with 3D scanning tools.

Over the past decade, the practice of architecture has radically transformed through the digital acceleration and sharpening of production. New architectural languages are being constructed through the conversation between material, tool and design intent. These advances represent an opportunity for architects to relocate themselves within the design space of the construction industry, back at the heart of the process. Whether a greater role in fabrication encourages better architecture is beyond the scope of this publication but we strongly believe this volume of case studies offers a compelling range of strategies for practice and academia to reflect and build upon.

RESEARCH PAVILION ICD/ITKE

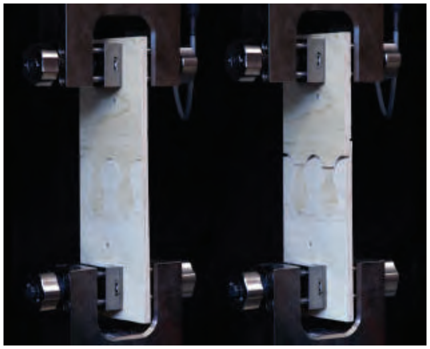
ACHIM MENGES, SIMON SCHLEICHER & MORITZ FLEISCHMANN,
INSTITUTE FOR COMPUTATIONAL DESIGN, STUTTGART UNIVERSITY

In 2010, the Institute for Computational Design (ICD) and the Institute of Building Structures and Structural Design (ITKE), both at the University of Stuttgart, designed, fabricated and constructed a temporary research pavilion. Demonstrating the latest developments in material-oriented computational design, material simulation and robotic production processes in architecture, the result is a 'bending-active' structure made entirely of robotically fabricated, elastically bent plywood strips. During its operation time the structure's material changes were documented, its geometry measured by 3D scanning and its structural performance validated by various loading test.

In today's practice, computational tools are predominantly employed to create design schemes through a range of design criteria that leave the inherent characteristics of the employed material systems largely unconsidered. Ways of materialisation, production and construction are strategised only after a form has been elaborated, leading to top-down engineered, material solutions that often juxtapose unfitting logics. Based on an understanding of form, material and structure not as separate elements, but rather as complex interrelations embedded in and explored through integral processes of computational design, the research presented in this project demonstrates the feasibility of an alternative approach to computational design. It unfolds morphological complexity and performative capacity from material characteristics and fabrication logics without differentiating between virtual form generation and physical materialisation processes.

RESEARCH GOALS FOR THE PAVILION

Material computes. Any material construct can be considered as resulting from a system of internal and external pressures and constraints. These pressures determine its physical form. In architecture, however, digital design processes are rarely able to reflect these intricate relations.[1] Whereas in the physical world material form is always inseparably connected to external forces, in the virtual processes of computational design form and force are usually treated as separate entities, as they are divided into processes of geometric form generation and subsequent simulations that are based on specific material properties.



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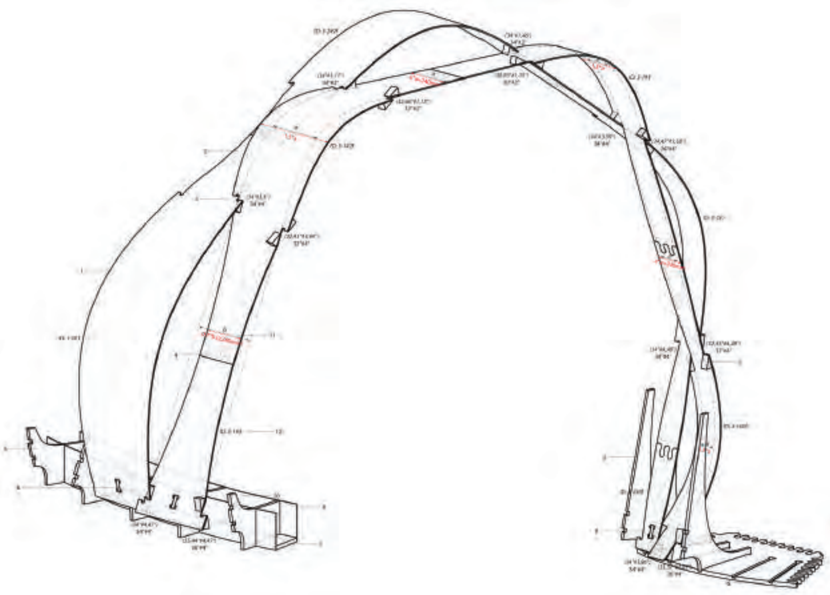

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Challenging this well-established approach was the starting point for the design, fabrication and construction of a temporary research pavilion.

In this context, the research pavilion demonstrates an alternative approach to computational design[2]: here, the computational generation of form is directly driven and informed by physical behaviour and material characteristics as well as by the fabrication constraints of the employed industrial robot.[3] The structure is entirely based on the elastic bending behaviour of birch plywood strips. These strips are robotically manufactured as planar elements and subsequently connected so that elastically bent and tensioned regions alternate along their length. The force that is locally stored in each bent region of the strip, and maintained by the corresponding tensioned region of the neighbouring strip, greatly increases the structural stiffness of the self-equilibrating system. In order to prevent undesirable local stress concentrations as well as the adjacency of weak spots between neighbouring strips, their couplings need to shift their locations along the structure, resulting in 80 different strip patterns constructed from more than 500 geometrically unique parts. The combination of both, the stored energy resulting from the elastic bending during the construction process as well as the morphological differentiation of the joint locations, enables a very light yet structurally sound construction. In this lightweight and pliable structure bending is not avoided but instrumentalised, here referred to as bending-active structure.[4] The entire structure, with a diameter of more than 10 metres, can be constructed using only 6.5-mm-thin birch plywood sheets with a total construction weight of only 400 kg. Furthermore, the extremely thin skin is not only a load-bearing structure but also a light-modulating and rain-protecting envelope for this semi-interior extension of the public square.

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1: Exterior elevation of pre-stressed plywood lamellas.

2–5: Fabrication details: Puzzle tension joints for strip segment connections, strip connection joint and base connection joint.

6: Script-based construction detailing for robotic fabrication, including relevant system joints.

7: Interior view of bending-active pavilion structure.

COMPUTATIONAL DESIGN & FABRICATION PROCESS

The fabrication process and the simultaneous assembly of the pavilion on-site were highly dependent on the use of the faculty's newly established Robotic Manufacturing Laboratory. All settings of the robotic arm as well as the spindle management (like routing speed, depth and feed motion) were adjusted to combine high accuracy with efficient logistics. Furthermore, the tight production schedule necessitated that, within one run, the entire part was not only cut in its contour but also screw-position marked, material layers removed and finished, as well as joint angles precisely shaped. Designing all these details to be fabricated by one and the same spindle with a diameter of 20 mm additionally reduced the production time. This method allowed the fabrication of 500 geometrical unique parts with three types of alternating connection details and about 1,500 different angle set-ups.

The development and construction of the research project allows for the verifying of the presented computational design and fabrication process by comparing the following three models: the computational design model, the related FEM model derived by structural engineers and the actual geometry of the constructed pavilion measured by geodesic engineers.

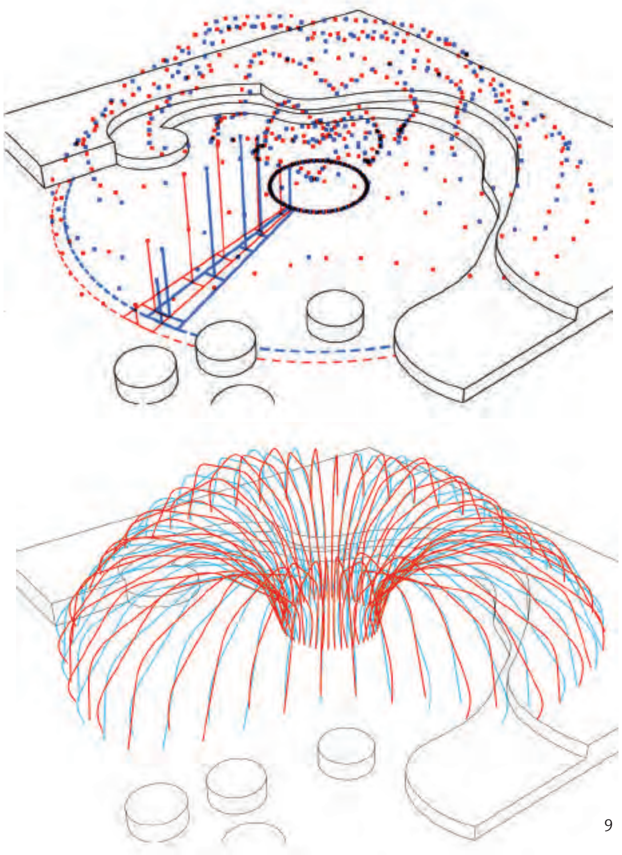
For the planning of the pavilion the computational design model was one of the essential interfaces that helped to coordinate and mediate various design and fabrication factors. In this model relevant material behavioural features were embedded in the form of abstracted geometric relationships that were transferred into parametric principles. Their interdependencies were defined through a large number of physical experiments that focused on measuring the deflections of elastically bent plywood strips. While this purely geometric model was, at this stage, an abstraction that neglected additional deforming influencing factors like the structure's dead load or external forces, it already gave feedback about the range of design possibilities reachable by this process. Furthermore, based on 6,400 lines of code, one integral computational process derives all relevant geometric information and directly outputs the data required for both the transfer into the structural analysis software as well as the manufacturing software of a six-axis industrial robot.

In the second stage a structural analysis model based on FEM simulations was used to calculate the actual material behaviour under the given geometric and physical conditions while also considering all acting forces and material limitations. Coherent with the

computational design model (see previous point), the input for the simulation was generated from the same integrative script. This input geometry consisted of developed surface-boundary curves, as opposed to a 3D solid model, which was generated for the design evaluation. In order to simulate the intricate global equilibrium of locally stored energy that results from the bending of each strip, the model needs to begin with the planar distribution of the 80 strips, followed by simulating the elastic bending and subsequent coupling of the strips to form a combined self-stabilising structure. The detailed structural calculations, which are based on a specifically modelled mesh topology that reflects the unique characteristics of the built prototype, also allows for understanding the internal stresses that occur due to the bending of the material in relation to external forces such as wind and snow loads – a very distinct aspect of calculating lightweight structures. Therefore, the structural analysis model allowed for both verifying the geometrical shape within predefined stress levels and material capacity utilisation, as well as analysing the deformations and stress distributions of external wind loads.

8: On-site assembly of the planar strips.

9: High-definition surveying of the tolerances in the pavilion geometry with a 3D scanner.



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The third model is a point-cloud dataset based on the exact measurement of the built prototype that was established through full-scale scanning and geodesic measurement techniques. It documented the pavilion's geometry and thus offered valuable clues to changes in the material at different stages during the pavilion's operating time. The significance of this last model is two-fold. On the one hand it helps to understand the precision and deviations of the two models explained above as compared to the built artefact. Thus, it provides the critical link between the (intentional) geometric model and the (pre-calculated) FEM analysis model. On the other hand it demonstrates the pavilion's structural performance over a longer time period by documenting the geometry changes resulting from the relaxation and creeping of the plywood strips. This information can be used to calibrate the FEM simulation and helps to predict the durability of other elastically bent wood constructions. In order to test this, additional loading-tests were conducted.

Finally, comparing the generative computational design process with the FEM simulation and the exact measurement of the geometry that the material, computed, on-site demonstrates that the suggested integration of design computation and materialisation is no longer a future goal but a feasible proposition.

THAW IMAGINING A SOFT TECTONICS

METTE RAMSGARD THOMSEN, KARIN BECH & MARTIN TAMKE,
CITA, ROYAL ACADEMY OF FINE ARTS

Architectural construction is traditionally realised through a compressive logic. The orthogonal geometries of the traditional drawing tools, the parallel rule and set square prioritise linear load paths, creating resonance between the tools of design and construction. As tools change with the introduction of computation this core relationship is challenged. Computational design tools and the introduction of programmable models allow for the proliferation of structural systems that operate outside the compressive. Here we look at a research in textile constructions at an architectural scale, exploring how friction-based structures can allow the realisation of a new pliable architecture.

Using the term 'soft tectonics', the research focuses on how friction-based structures engage material performance and how computational design strategies can employ these strategically. It asks: how can textile principles suggest new ways of thinking about structure on an architectural scale? If structure becomes soft, how can the integration of movement allow a suggestion of responsiveness and adaptability? And finally: what would it be like to live in a soft space?

As a wall membrane, Thaw explores the making of a pleated structure, using textile concepts of friction and tension for tectonic structures of architectural scale. Thaw is made of ash slats braced together by steel joints. Each slat is bent into shape, pressing against each other and creating an internal friction. While each single component is inherently weak, the load forces move through a field of friction-based interconnectivity by which the overall structure becomes stiff. This integral weakness allows the structure to retain a measure of pliability or *softness*, allowing it to adjust to changes in its environment or load. Making use of the material performance, the slats utilise the particular straightness of grain found in Ash timber, allowing for construction with a minimal thickness and a high degree of pliability. Examining the idea of 'soft tectonics', through an adaptable structural system by continually adjusting the tension wires that run through the structure, Thaw is animated. The tension wires are connected to a simple pulley system that alternately tightens and relaxes it, creating an internal rhythm of expansion and contraction, in resonance with its inherent material performance.

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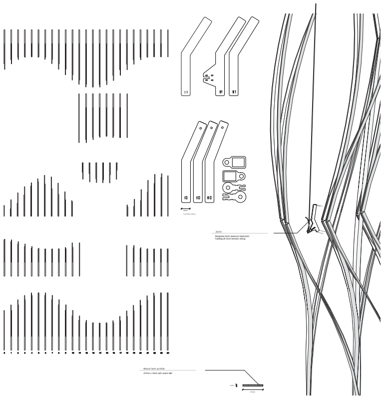

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1: Thaw installation, incorporating a second skin as a pleated manifold.

2: Developing the material simulation.

3: Defining for digital fremstilling.

4: Plan view showing the complexity of multiple material layering.

As an architectural installation Thaw furthers this examination of a structural system through the integration of a second skin, thereby addressing the question of enclosure and the assemblage of multiple materials. A pleated manifold is tied to the structure, creating a diaphragm surface that expands and contracts. The textile developed in collaboration with North Carolina State University, College of Textiles,[1] is stiff yet pliable, creating a degree of structural independence while enabling the structure to move. The skin is further detailed through vertical perforations and embroidery, allowing the surface a further degree of horizontal stretch while also strengthening the material across the length of the surface.

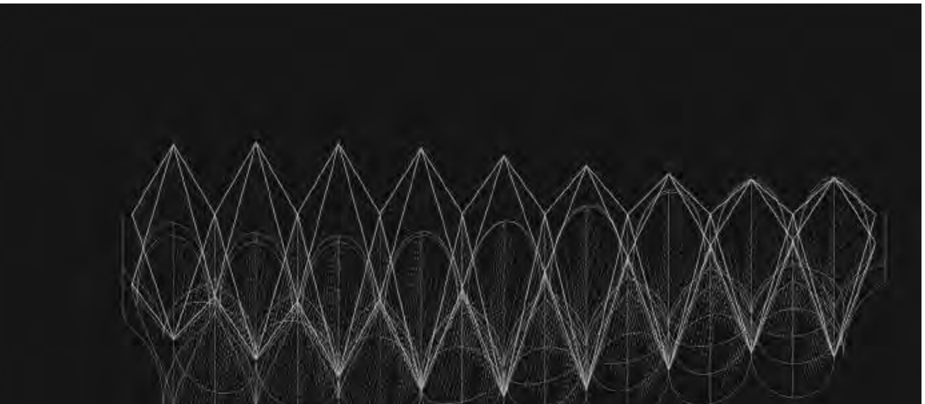
RESEARCH ENQUIRY: DESIGNING FOR MATERIAL PERFORMANCE

In the creation of a textile surface at an architectural scale, Thaw follows on precedents set by projects including early geodetic aeroplanes[2] as well as the light metal lattice structures of the late nineteenth century by the Russian engineer, Vladimir Shukhov.[3] These structures diagonally spin thin wood or metal slats into hyperboloid drums pushed out by horizontal circular members. Each crossing of the slats is connected, thereby creating an integral stiffness to the structure while also using minimal material. The structures are essentially self-bracing, pressed into tension.

Inspired by these structures, Thaw creates a new level of formal freedom using computational modelling and digital fabrication technologies. A key aim in the research is to explore how computation in design systems can include the simulation of the material performance and incorporating this as an integral part of the process. Based on a set of tracings of the material deformation, a simulation of the bending geometry was developed by calculating the changing relationship between length and bend.[4]

The structure is designed around a set of defined contour lines where each slat is vertically sliced, allowing for the interwoven pleating of the structure as a formal double weave. Developed using simple parametric tools, the contour lines act as guides, defining the individual length of each of the slats as well as the angle of each of the steel brackets. The shape of the structure results from these interrelationships. The design of the structure lies therefore with the detailed definition of the contour lines that, in turn, set up the fabrication drawings for both the machinic laser cutting of the steel brackets as well as the workshop drawing for the table sawing of the individual wood slats.

The model is also used to generate the complex and non-standardised textile patterns of the second skin. The incorporation of a parametric model, of geometric deformation caused by material flex, generates the flat pattern-cut textile skin. The model therefore has a two-fold role. On the one hand it acts as a purely relational composition that allows the measurements of lengths and angles. On the other, it can be used to simulate the material deformation so as to provide the geometry by which the second skin is constructed.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ENGAGING PERFORMANCE THROUGH ACTUATION

In Thaw the attention to the pliable and the soft is further accentuated through actuation. The motion is understood as a continual internal re-calibration of the structural load bearing. The structure is therefore not responding to a change in the outside environment but, rather, seen as an animate that pulses continually, changing the state of the material flex. The structure moves in much the same way as a longbow. A set of servo motors are mounted above the structure, pulling the tension cables that are threaded through it. Much like a longbow, the diagonal relationship between the tension cable and the structure allows a small amount of actuation – the tensioning of the cable by 50 mm – to have a large effect on the structure – the horizontal flexing of the slats by 250 mm.

CONCLUSIONS

Thaw negates the primacy of the static and the permanent, instead suggesting an architecture of change and continual renegotiation of the structural loadpaths. Actuation is seen as way of questioning what happens as structural systems come to engage material performance. As such, many of its propositions remain speculative and suggestive, but as a research probe it asks some interesting questions about what a soft architecture might be: what would the boundaries be and how could we develop design strategies for designing across time? As a tectonic investigation, the work prototypes pleating as a friction-based structure finding textile systems that allow for lighter and less materially intense structures to be imagined. The incorporation of parametric modelling of geometric deformation resulting from material flex is employed as a means of creating the geometry needed to specify the second skin. As such, the material modelling is used to address the structure's further realisation of enclosure and material assembly as well as exploring the incorporation of material performance as part of a total design system.

In parallel projects CITA is investigating how a structural analysis of material performance can be incorporated into the geometric design models and to create feedback between structural analysis and design as well as between design and digital fabrication. Through a collaboration with SIAL[5] there is the intention to develop a structural design that interfaces finite element material modelling with parametric modelling of a design system. By moving from geometric to material simulation it is CITA's aim to employ material performance as an integral part of overall structural performance towards the development of lighter building systems.

FABRICATING INDETERMINATE PRECISION

NAT CHARD,
UNIVERSITY OF MANITOBA

The medium with which we draw can play quite different parts in our work. At one extreme, when a flash of inspiration enlightens us, the role of the medium is to translate the thought unsullied into a state that others can understand and discuss. At the other, a seemingly insubstantial idea may be nurtured and productively corrupted by the capacity of the medium, helping the idea to emerge into something of substance. Temporally, one is about the instant, a completeness. The other is about duration and a state of contingency. This proposal is about the latter: fabricating drawing instruments to draw out an indeterminate condition, both in the architecture that is depicted and in the act of making the drawings. This may seem paradoxical until we look at how prescriptive the mechanisms and conventions of architectural drawing have become, especially with all the helpful features in digital drawing and modelling programs that anticipate the things architects typically do.

Immediately there is a question of how the instrument should be drawn. Acknowledging that all instruments are in some way prescriptive, this series of six types

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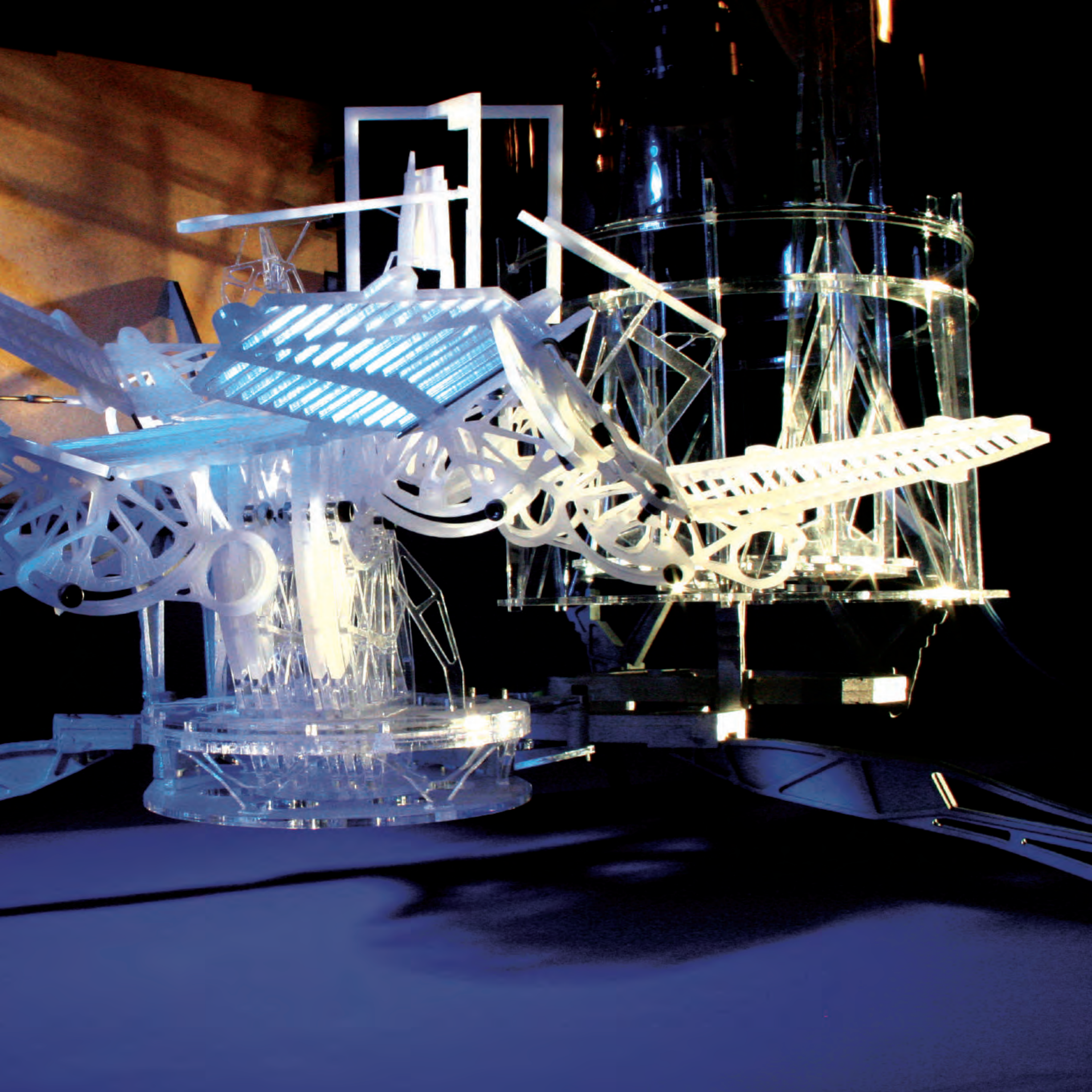

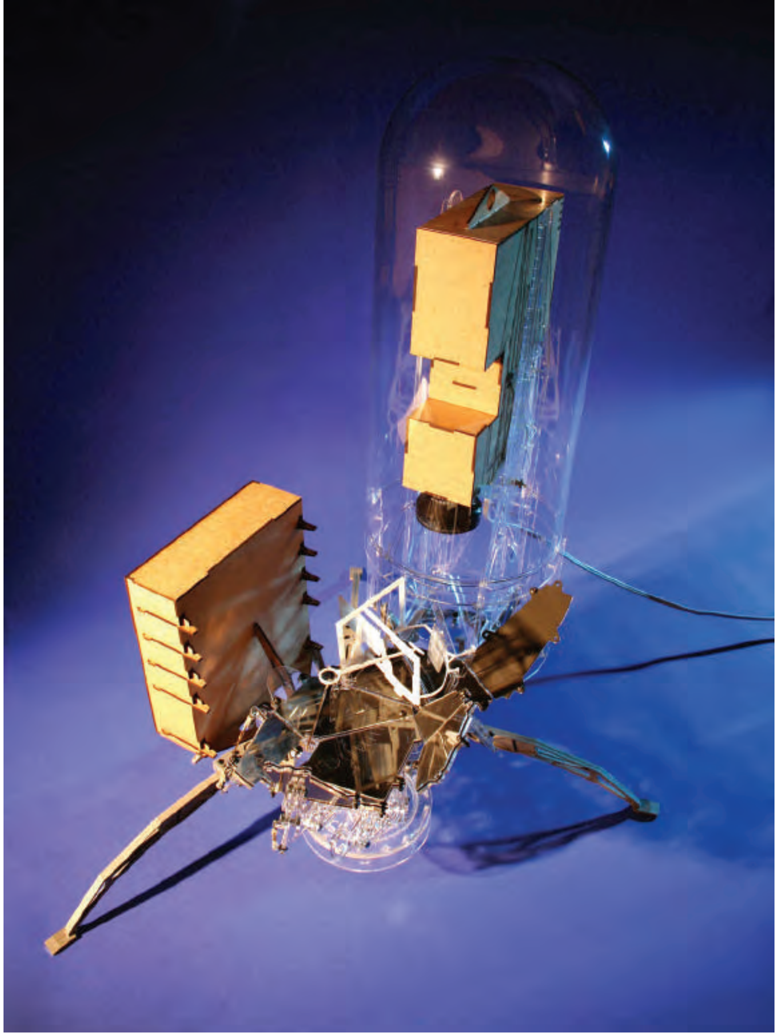

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1–2: Drawing Instrument No. 3.

3: Drawing Instrument No. 2, picture plane.

4: Drawing Instrument No. 2: an illuminated model in a box (inside the glass dome) is projected via a lens from a 5 x 4 camera onto a folding picture plane.

of drawing instrument are all drawn on computer and use computer-aided manufacturing techniques – CNC milling and laser cutting. The differences in manufacturing processes had consequences on the way the instruments were designed.

How does one go about designing and making a precise instrument for drawing in an indeterminate way? Certainly the approach to designing the instrument is different from that of working the completed device. The question is complicated by a situation where the full performance of the instrument is not known when work is started. If we were designing a camera and we knew the nature of the lens and the format of the film, we could design a camera body to precisely relate the two. If we want to play with lenses and a screen to resolve an image we can work with an optical bench that sets up certain parameters of relation but allows adjustment for precise alignment and position. The instruments play between these two, providing as precise an armature for those parts that are known in advance and enough provision for adaptation and improvisation.

The practice of designing as you go along evolves with the different processes used to manufacture the instruments. For the first three devices there is a cast frame, as well as for almost all the active components for the first instrument. The patterns for the pieces were drawn on computer and cut using a simple pocket clearing program and CNC milling machine. The slowness of the process allowed subsequent pieces to be designed while the previous piece was being milled. The only allowance that needed to be made for the future pieces was an overall sense of the thing (but not a design) and the geometry and dimension of the joints between the pieces. Working like this was possible due to continuous availability of the mill. The benefit was that each piece could respond to reflection on the last as well as the accumulation of understanding that came from using the process. When all the patterns were made, silicon rubber moulds were formed from the patterns to cast plastic pieces

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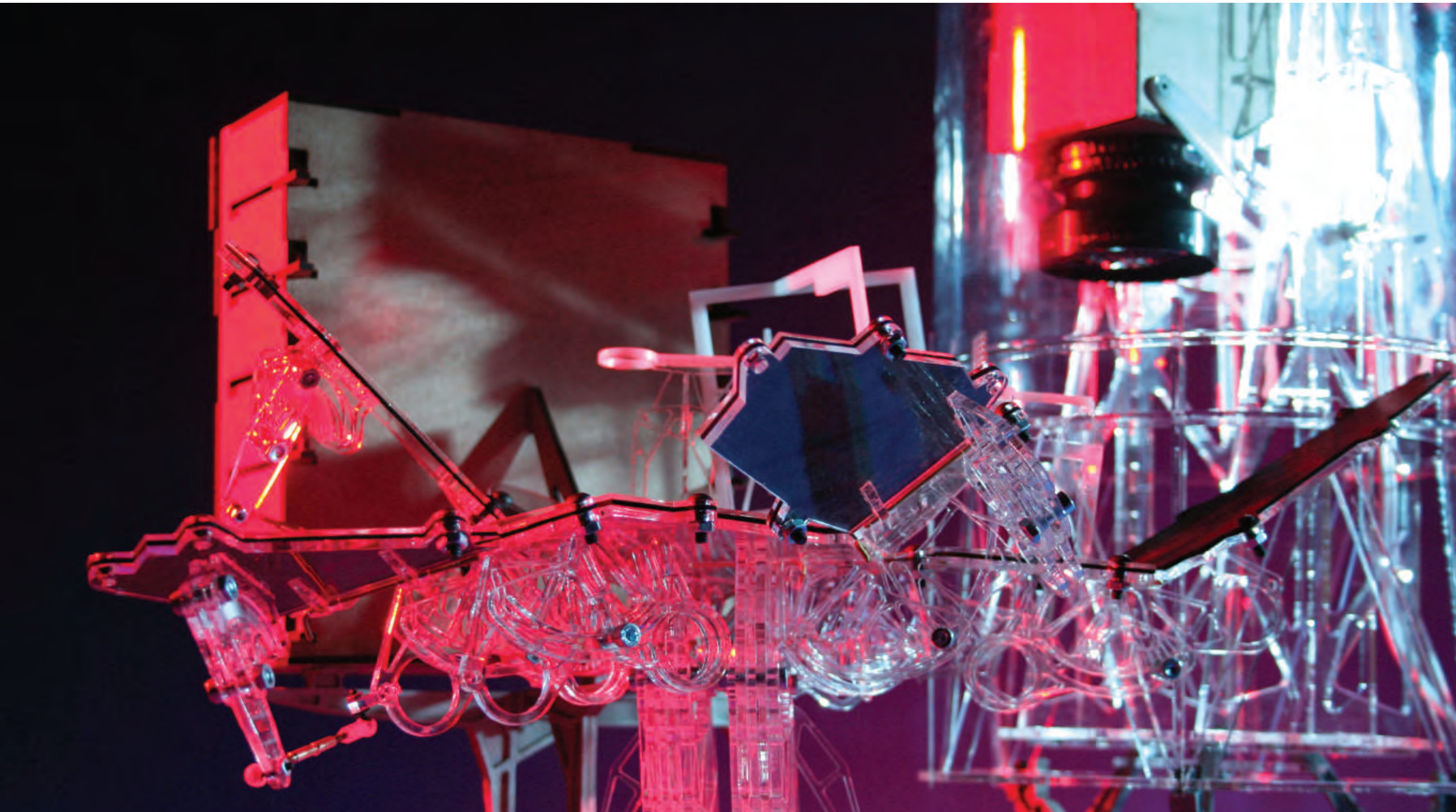


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for instrument one, and lost wax pieces for subsequent investment cast aluminium components for instruments two and three.

The rest of the components in instruments two and three, and almost all of the subsequent instruments, are made on a laser cutter. The tool was not as constantly available as the CNC mill was, and for efficient use of a sheet of material, many components needed to be cut at once. The process is significantly quicker than milling and casting, encouraging a more iterative way of working in contrast to the evolutionary design process (within the same device) when milling, as well as a more time- and cost-effective way of making multiples with slight differences. As more is known about what the instruments have to do, a knowledge gained from the previous iterations, it is also possible to design a larger proportion of the thing in advance, rather than discover it through the process of making. With the increased understanding of what the active drawing components needed to be and do, the instruments shift from having a flexible support (like an optical bench) to a more specific mount, for instance like the dinosaur armatures that hold a particular set of bones in a certain position. As an instrument makes connections between content and technique, it also makes indeterminate instruments appear problematic. This work turns this potential problem around and exaggerates it. In a discussion of how Rimbaud constructs his engagement with the reader in *Illuminations*, Todorov explains:

> The phrases themselves that constitute the text are quite comprehensible, but the object that they evoke is never named and one therefore hesitates as to their identification … the interpretative process is radically changed when symbolic evocations, however ingenious, find themselves deprived of a pedestal.[1]

It is a tactic that these instruments learn from. They are not just instruments but appear to be didactic devices that clearly make sense. What they make sense about is not stated, although there are enough provocations for those that engage with the instruments to imagine what it might be. The latent prescription of the instrument is therefore about the structure of making sense rather than the specific content of the object. Instead of being prescriptive, or closing the meaning of things, these apparently didactic instruments in fact aim to keep meaning alive and open. In terms of the meaning of making and how we decide what to make and how to make it, the instrumentality of the tool is brought into question.

The architectural drawing rehearses the thing that will be built but the engagement one has with the drawing is very different from the proposed engagement with the thing that is drawn. The drawing instruments in this research operate between drawing and making, witnessing the emergence of the 3D from the 2D or the drawing becoming space. In all the instruments this happens through the folding of the picture plane. The fifth instrument which draws by throwing paint, also builds as it draws. Other similar instruments (to the one receiving the paint) throw the paint as a means of discussing content within the project. A figurative model of the situation relevant to each instrument is protected under a glass dome to remind the person drawing what is at stake.

5: Drawing Instrument No. 4 (Prototype for instrument No. 5): one chassis holds a (red) paint-throwing catapult that has a range of adjustments for angle and trajectory. The other holds a model above and in front of a folding picture plane that is covered by a sheet of paper to receive the paint.

6: Drawing Instrument No. 5: orange paint is captured flying though the model in this high-speed photograph.

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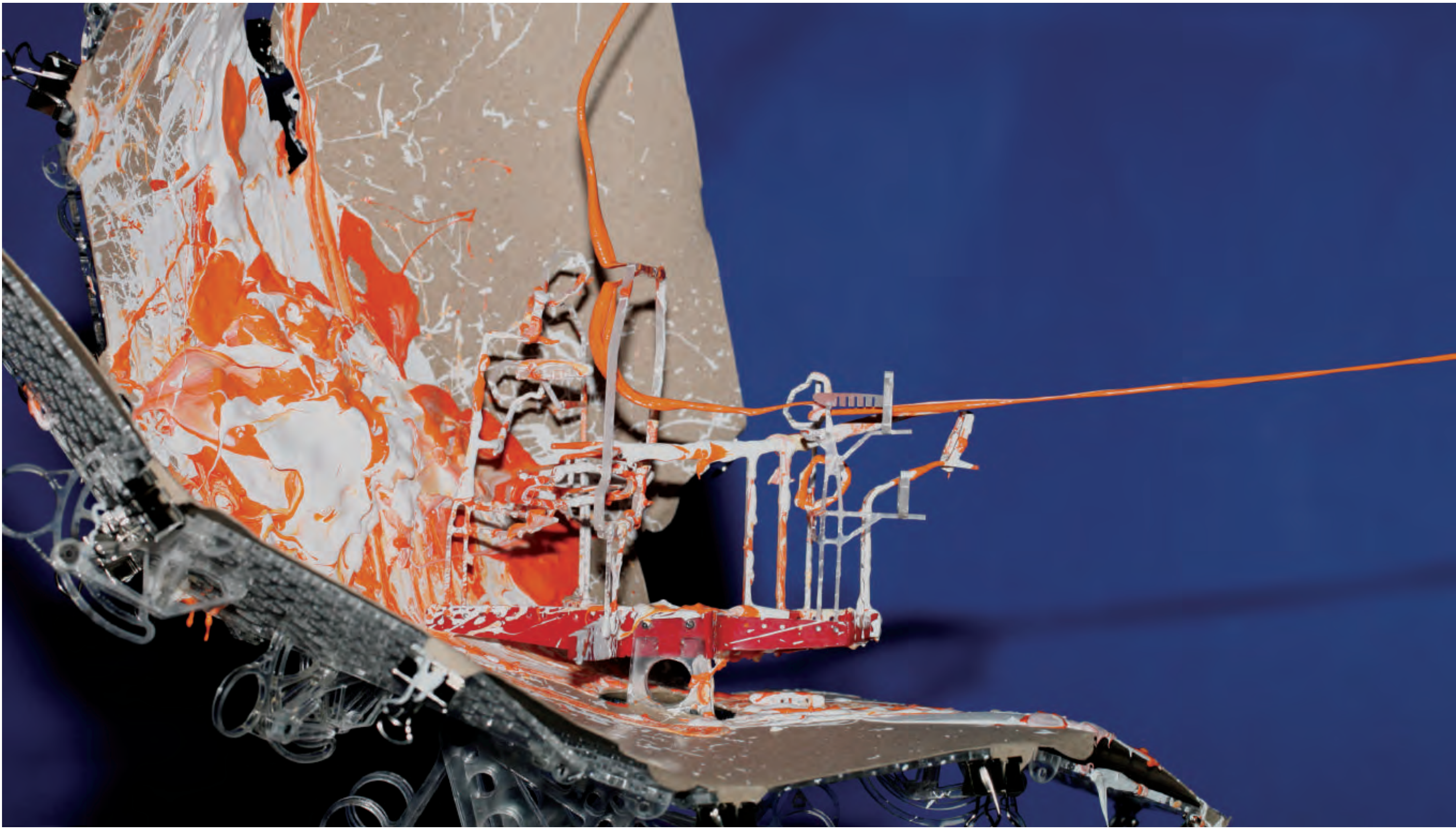

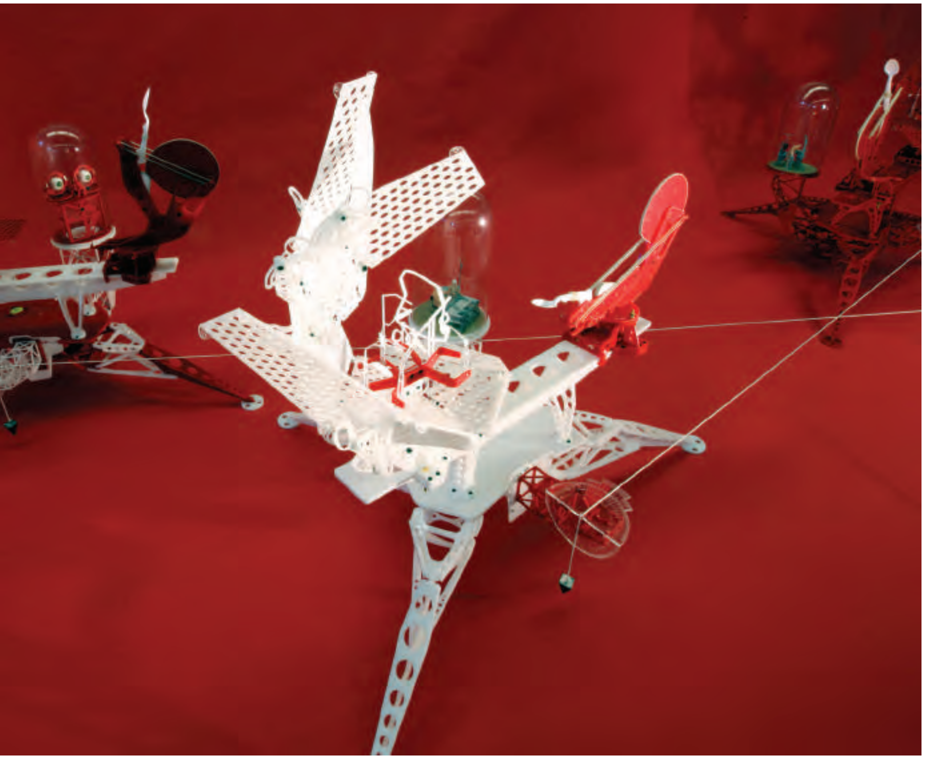

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7: Drawing Instrument No.5. A group of instruments ready to draw on one another.

8: Drawing Instrument No.6 projects shadows onto a folding picture plane and is able to then float that shadow in mid air.

As the paint is thrown it collides with a group of abstract models that deflect the paint before it hits the picture plane (that sits behind and below the model), casting a shadow of paint displacement rather more than the figure of the model. The abstract model parts both represent the situation shown in the figurative model and have a physical performance with the paint. As well as deflecting, they also gather so that the accumulation of paint develops the pieces in relation to the history of discussions between the instruments. Some of the elements have serrations so that they hold onto the paint, similar to the way in which more developed pasta shapes hold onto their sauce. The paint builds up on the model and changes its performance, both in terms of the deflections and paint gathering, as well as its formal characteristics.

As methods of fabrication, the milling and cutting operations can be scaled to building-sized manufacture but the accumulation of paint on the model armature does not represent a scaled-up process. The milling and cutting tools reproduce geometries set out in computer drawings with a high degree of precision, but those drawings, as explained earlier, only have an emerging precision to the idea. Although the paint-throwing catapults have an accurate aim, their full performance has a low precision of predictability in terms of what will take place in each throw (the reason for using the medium). On the other hand, the accumulation of paint and its dispersal on the picture plane has the highest precision with respect to the idea.

In an inversion of the familiar relationships between idea and technique, with the highest manufacturing precision meeting the greatest uncertainty (and vice versa) the precise manufacture of the imprecise idea is not in vain. The authority given by apparently didactic instruments provides license and latitude for the drawings to find a conceptual precision. The appearance of precision in the uncertain instrument encourages the sense that the indeterminate drawings that it produces have precise meanings without stating what those meanings are. The instrument encourages that observer to construct those meanings with the assurance (through its apparent precision) that those meanings must be worth teasing out. It is the fabrication of a seduction.

(FAB)BOTS CUSTOMISED ROBOTIC DEVICES FOR DESIGN & FABRICATION

MARTA MALÉ-ALEMANY, JEROEN VAN AMEIJDE & VICTOR VIÑA,
AA, IAAC

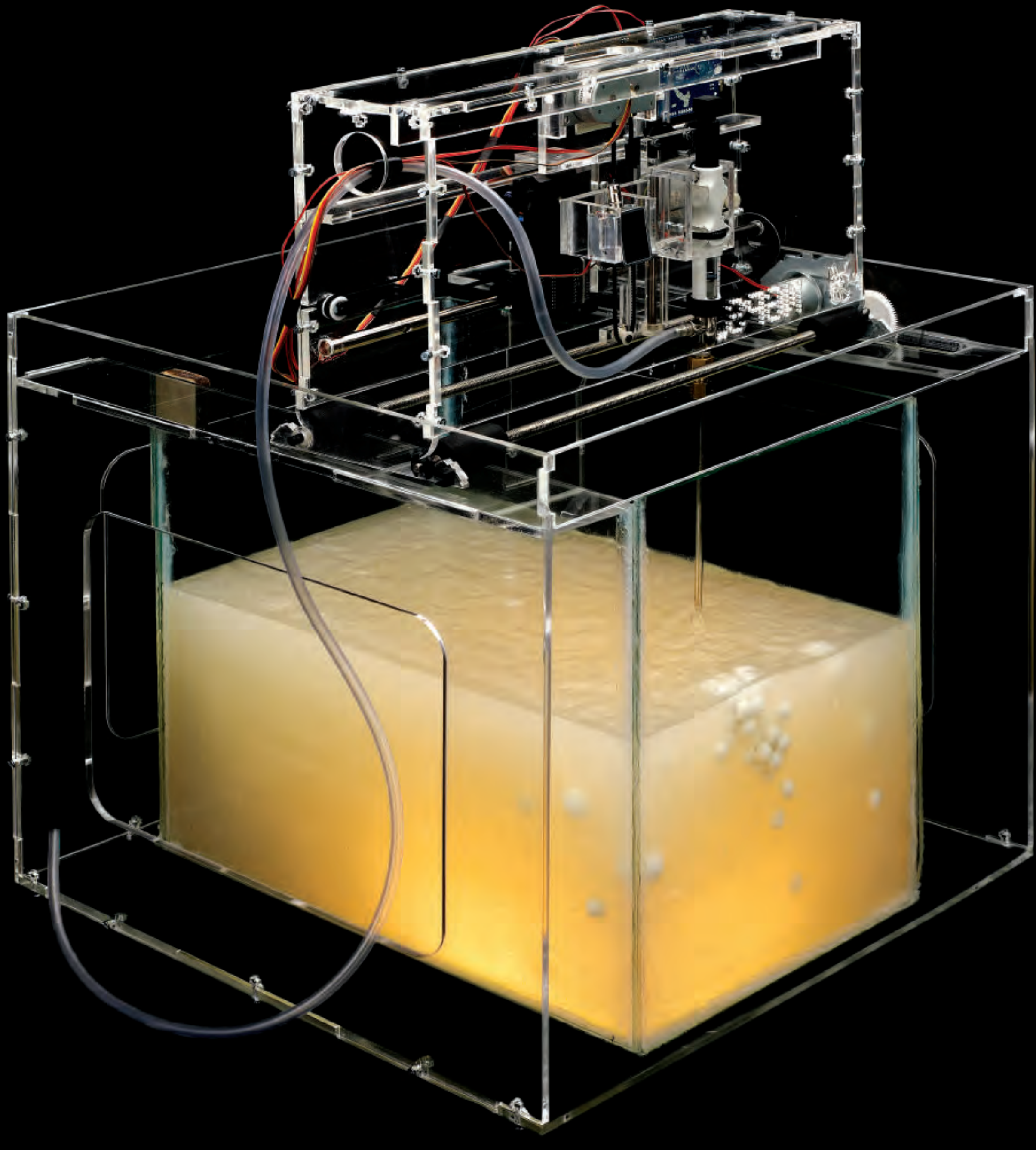
Digital design and fabrication technologies have given architects the means to invent new architectural languages and communicate them directly to production facilities, allowing for the construction of projects with unforeseen complexity. Yet the impact of digital fabrication goes far beyond the mere production of complex geometries.

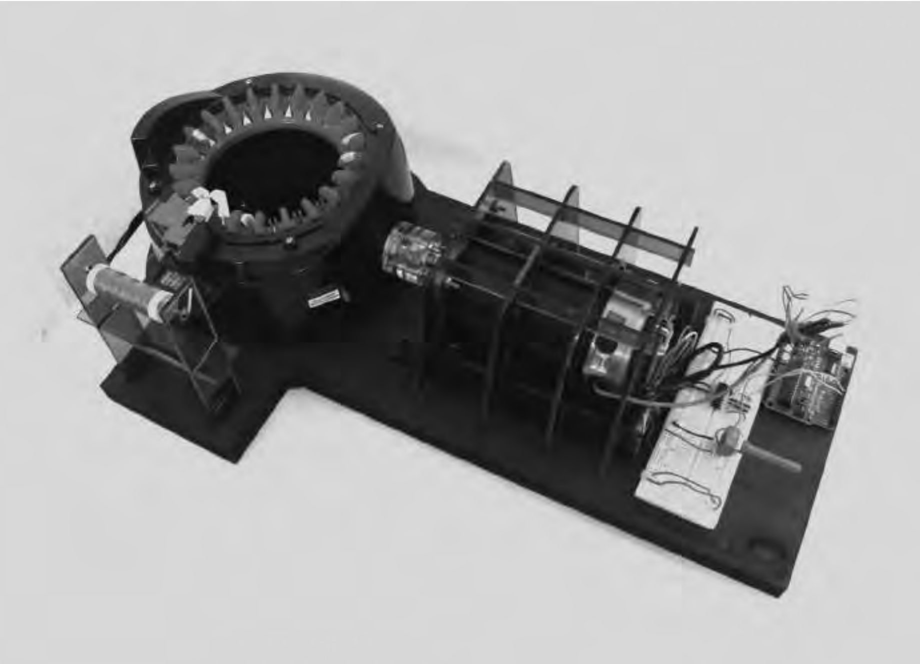
A growing number of architectural practices and academic research groups are exploring the new-found freedoms in the close connection between digital design and production, inventing new design processes, material applications and building scenarios based on opportunities found within the use of digital fabrication technologies.[1]

The work presented in this article fits within this context, but it also explores which opportunities lie beyond the use of existing CAD/CAM technologies borrowed from other industries. Focusing on technologies and workflows that are specifically designed for architectural production, it considers the design and operation of custom fabrication devices as an integral part of the design process. Exploring new scenarios for the creation and inhabitation of architectural structures, it experiments with flexible, mobile and low-cost fabrication machines. This allows the work to speculate about projects that are site-specific, customised and adapted to local climatic conditions, in areas and communities that traditionally have limited access to new technologies and infrastructure.

This article presents a collection of ten projects that investigate the workflow between computational design and material production methods, through the invention and development of customised, numerically controlled fabrication devices, software protocols and material solutions.

The ten projects are conceived by master students in the DRL graduate programme at the Architectural Association (AA) and the MAA programme of the Institute for Advanced Architecture of Catalonia (IAAC). They were developed in two design studios tutored by Marta Malé-Alemany, in collaboration with Jeroen van Ameijde (London) and Victor Viña (Barcelona).[2]





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1: Non Gravity Printing Systems: machine prototype.

2–4: Dreamweaver: hacked household knitting machine, knitted tube typology studies, structural prototype.

METHODOLOGIES FOR EXPERIMENTATION

Using introductory tutorials focusing on scripting and machine building, the design studios encourage students to formulate a critical position towards the characteristics of existing digital fabrication technologies. The studios develop early prototypes of custom-designed fabrication systems, using techniques such as the 'hacking' of standard CNC machines, consumer devices or electronic toys. These 'quick and dirty' tests help to explore the behavioural properties of the proposed hardware solutions, opening up new lines of research and discussion, and provide the basis for successive generations of system designs. Emphasis is placed on the different nature of the abstract machinic models of the proposals to their implementations as prototypes, discussing the economy of means in applications at a larger scale.

Developing devices in combination with specific methods of material formation, the studios explore integrated design and production methods that are specific to a particular application scenario. Suitable for deployment on-site, these methods are potentially more viable to be used in architectural projects than standard digital fabrication technologies, which are designed for the mass production of a generic range of products in an industrial setting. The students' prototypes of fabrication devices deliver proof of concept for the possible implementation with a small investment of time and resources. The limitations of the relatively simple machines are regarded as an opportunity to develop new architectural languages, emphasising the scenario as an optimisation between the characteristics of specific materials, tools and design.

As the studios emphasise the testing of deployment scenarios through material and mechanical testing and digital simulations, students are asked to reflect on the implications of their tools for the nature of the architectural design process itself. Several new processes of conception and production are emerging within the work, ranging from methods of direct control – in which digital fabrication comes after a customised design process – to methods of indirect control, where the final product emerges out of the interaction between fabrication devices, material behaviour and environment.

PROTOTYPING ARCHITECTURAL MACHINES

Design and build processes using direct control take advantage of the possibility of traditional numerically controlled devices to activate a number of motors with high precision using relatively simple code. A number of student projects have started with the adaptation of the components of a CAD/CAM system and its computational workflow, which translates parametric coordinates to digital signals, which in turn drive electromechanical actuators. Instead of using the motors to drive linear axes in a way that is standard in two- or three-axis CNC machines, they can be used to drive rotational devices, allowing to design custom machines with a more simple mechanical layout or to connect the motors directly into other mechanical devices.

Dreamweaver departs from hacking existing circular knitting machines with numerically controlled plug-in devices. The project's aim is to create alternative patterns, which serve to produce multiple variations of the common tubular knitted profiles. Using the variations in knitting patterns to produce structural elements for architectural applications, the machine is regarded as a part of a high-speed, on-site construction system.

Learning from typologies of branching propagation and hierarchical clustering, the project is developed as a computational and material model that operates at multiple scales. Using the precision made possible by the machinic system, the system is able to create varied structural typologies on a macro level by programming material patterns at the knitted micro-scale.

Fibr(h)ous(e) also uses CNC technology at its basis. Envisioning a foldable machine that can easily be transported on-site, a tabletop proof of concept

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machine built by the students is used to demonstrate the principles of filament-winding and explore the potential of using parametrically generated patterns of thread by driving the machine in various sequences of movements over time. Conceived as a combination of scaffold and skin, the project speculates on a fast deployment system for lightweight, self-sufficient living units that could be built in one day. Driving differential fibre patterns through structural, programmatic and climatic parameters in accordance with the required performance criteria for each living unit, Fibr(h)ous(e) proposes an efficient building technology based on the use of minimal material and an intelligent distribution logic.

PROTOTYPING WITH MATERIAL BEHAVIOUR

Taking advantage of the capacity of numerically controlled devices for the precise implementation of large datasets of machine instructions, a number of projects are also relying on complex material behaviour in the realisation of their final structures. Using both conventional and unconventional materials in innovative applications, these projects question the necessity to control all aspects of the material formation with the same precision, accepting the inherent limitations of a material or using its potential to self-compute for the benefit of the final structures.

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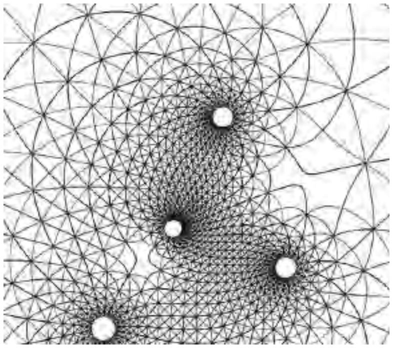
Sandbot explores low-cost casting processes using sand as recyclable formwork to produce building components. It is conceived as a portable device with multiple tools to carve and press sand that is available on-site into complex moulds, in which different materials can be cast such as plaster and cement. Within the constraints of the material and the tools the system is capable of infinite variation, as the mould is essentially scale free and completely reusable.

Non Gravity Printing Systems (NGPS), uses a multi-material deposition machine that releases small drops of paste-like materials into a chemical solution that causes the deposited liquid to form into perfect spherical droplets. The concept of the project grew out of the 'Molecular Gastronomy' experiments by Ferran Adrià, the famous head chef of El Bulli restaurant. NGPS operates in an environment that is nearly gravity-free because drops of material remain suspended until solidification is completed. This process of fabrication, based upon aggregation of small material deposits, allows for the combination of different materials according to performance criteria, resulting in highly complex structures with intricate material combinations.

PneuMorphosys explores the possibilities of incorporating air into the construction process as a structural optimisation, material distribution and morphing agent. The project uses a flexible formwork and a system of digitally controlled valves to regulate the flow of air into a series of discrete pockets, located inside and outside the structure to define both internal chambers and the external shape of the cast. A series of sensors serve to control the material pressure, allowing the optimisation of material distribution within complex formations.

Digital Vernacular is based on the use of a numerically controlled device to deposit paste-like materials such as clay. Following the geometrical rules dictated by material behaviour, a layered process of deployment is integrated into the design and construction strategy for housing units on-site. Adapting each design to the specific characteristics of its site, the project uses variable



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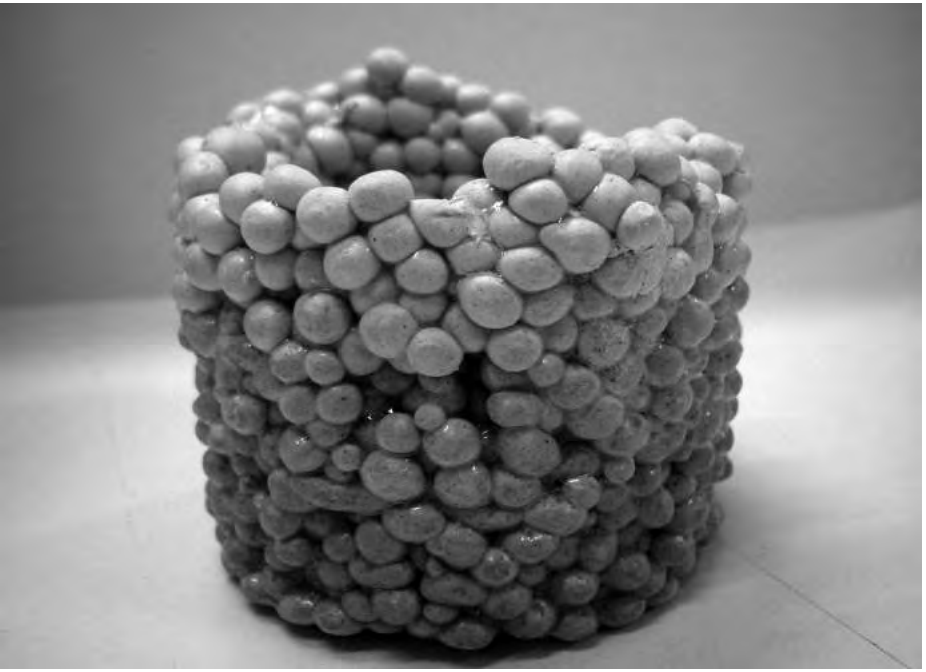

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5–6: Fib(h)rous(e): prototype detail showing scaffold and skin, housing scenario rendering.

7–8: Non Gravity Printing Systems: printed materials tests, multi-material printing logics.

patterns to incorporate openings for ventilation, circulation and views. In an on-site machine deployment scenario, the self-same rules that govern the construction sequence of co-dependent spaces is also be applied at the scale of a community, delivering vernacular housing environments at an equilibrium between materiality, fabrication and design.

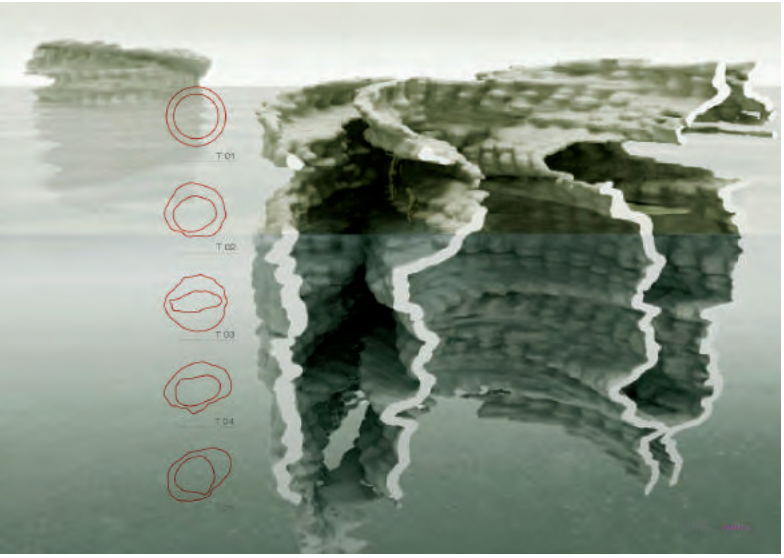
PROTOTYPING EMERGENCE

A number of projects investigate the emergent nature of decentralised computational models and their ability to perform according to intelligent behaviours, often mimicking processes of self-organisation as observed within nature. Providing an alternative approach to the design of custom hardware solutions, by using external sensorial inputs to adjust their fabrication process in real time, these proposals are based on adaptive, dynamic processes reacting to environmental conditions in order to construct highly performative and site-specific formations.

Fab(a)thing is developed as an instantaneous on-site design and fabrication process, using an infrared input device, a 3D positioning system and a deposition nozzle for PU foam, a material that solidifies almost instantly. Using an infrared distance sensor attached to the dispenser head to dynamically autocorrect its path, the system can respond to design changes or material deformation during construction. Conceived as an interactive CAD/CAM process that allows the end-user to sketch on-site in an augmented reality interface, the project opens up new paths to explore the application of emergence, decentralisation and adaptivity in alternative construction processes.

9–11: Fluid Cast: digitally simulated formation of a floating structure, prototype machine for plotting wax in water, numerically controlled printed wax prototypes.

12: HelioBot: mechanical prototype.



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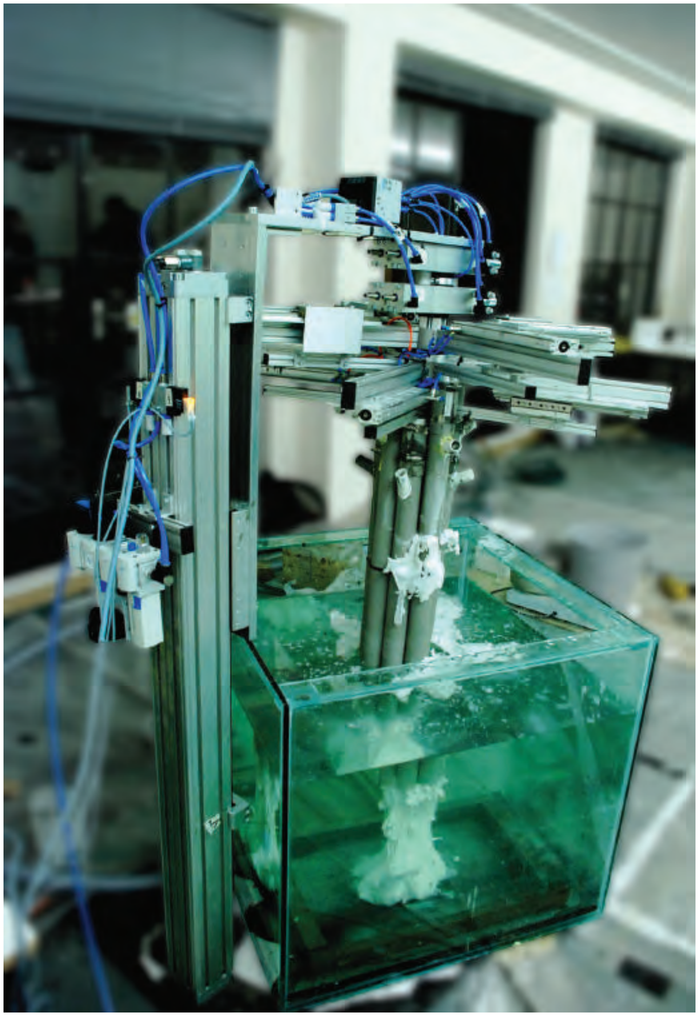

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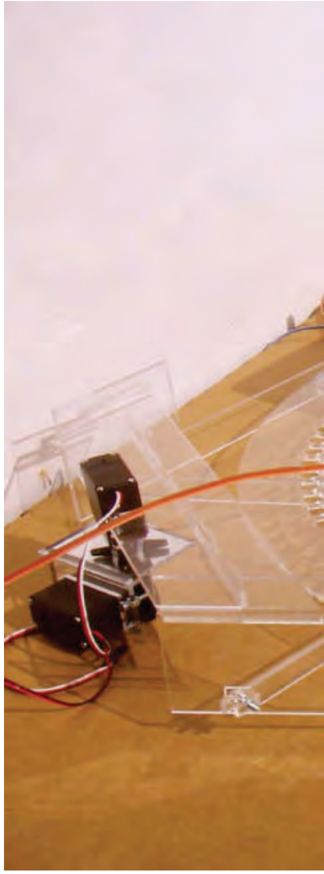

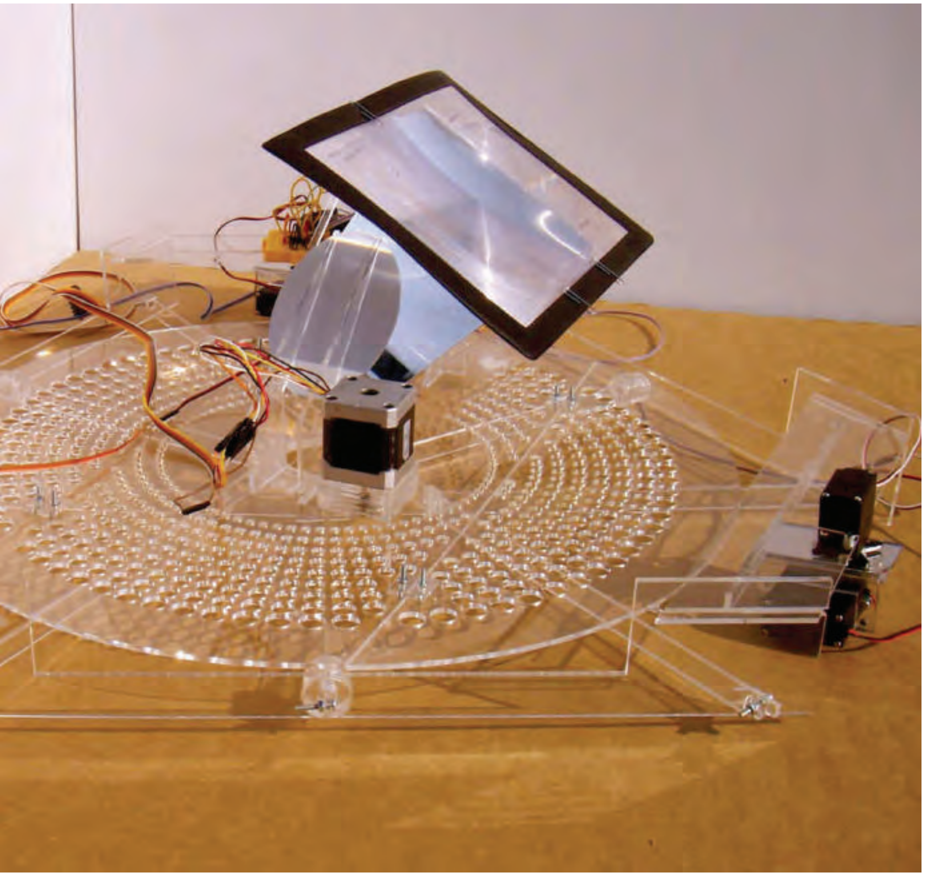

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Heliobot is a full-scale prototype of a solar-powered machine for on-site fabrication, capable of operating autonomously. It utilises no additional energy other than that gained from the sun and operates by concentrating solar energy for burning, heating and cutting in the preparation of materials for future assembly. The device operates as a mobile robotic system using light sensors, DC motors and simple analogue electronic circuits based on differential behaviours (as in Mark Tilden's BEAM robotics[3]). A sun-tracking system, comprised of four independent sensing and actuating modules, is able to align a Fresnel lens in order to achieve maximum solar concentration.

Mimicry is a project that explores the nature of flocking behaviour and swarm intelligence, using both software and hardware prototyping tools to explore computational models (as in Braitenberg's Vehicles[4] or Craig Reynolds' B.O.I.D.S.[5]). It simulates the collective result of a number of actuating agents over different lapses of time, generating material formations dependent on light conditions within a specific environment. The project speculates on new fabrication processes that simultaneously design, optimise and fabricate, producing emergent material patterns from simple governing rules as the machines operate over time.

Fluid Cast investigates complex material behaviour of phase-change materials as well as construction technologies using multiple material deposition agents, speculating on highly innovative fabrication scenarios for water-based structures. An extensive series of material tests is used to inform agent-based digital simulations that demonstrate how complex structures can be formed as a result of interactions between multiple machines and a dynamic 3D environment such as the sea. The emergent properties of these structures are generated through the method of controlling the devices, programming specific behavioural rules that are aimed towards performance criteria of the resulting structures within the environment in which they operate. The project tests the implications of behaviour of the deposition nozzles moving in-between short and longer distances from each other, creating instant networked structures that can be applied in various water-based and inhabitable applications, at a range of different scales.

DIRECTIONS FOR FUTURE RESEARCH

Through the development of innovative material processes, devices and computational methods, the students' projects speculate on application scenarios that distance themselves from current processes that are based on linear file-to-factory methods and industrialised modes of production.

The work employs high-tech software and hardware applications to enable deployment in relatively low-tech environments and communities, considering energy use and the economy of materials in using local resources in designs that are adapted to local contexts and climate.

Continuing to pursue a sense of realism through the demonstration of working machinic prototypes, rigorous material testing and digital simulations, the studios are currently developing new projects that cover a range of interests. Aiming for the construction of larger prototypes that test real architectural performance, the studios continue to set up design processes that are aimed at producing structures with a built-in intelligence, helping to address some of the new and pressing challenges of our time.

LOGIC MATTER

SKYLAR TIBBITS,
MIT

Given the increasing complexity of the physical structures within our everyday environment – buildings, machines, computers and almost every other physical object that humans interact with – the processes of assembling these complex structures are inevitably caught in a battle of time, complexity and human/machine-processing power. If we are to keep up with this exponential growth in construction complexity we need to develop automated assembly logic embedded within our material parts to aid in construction. Logic Matter is a system of passive mechanical digital logic modules for self-guided-assembly of large-scale structures.

Logic Matter explores the nature of assembly, specifically in the context of complex structures, i.e. assemblies with extremely large numbers of parts, assemblies with extremely small parts in large numbers or any possibility in-between. The problem that arises from geometric complexities and difficulties in assembly techniques include: material tolerances; error propagation; difficult construction sequences and the increasing complexity of the information required to build complicated structures. Many of these assembly problems relate

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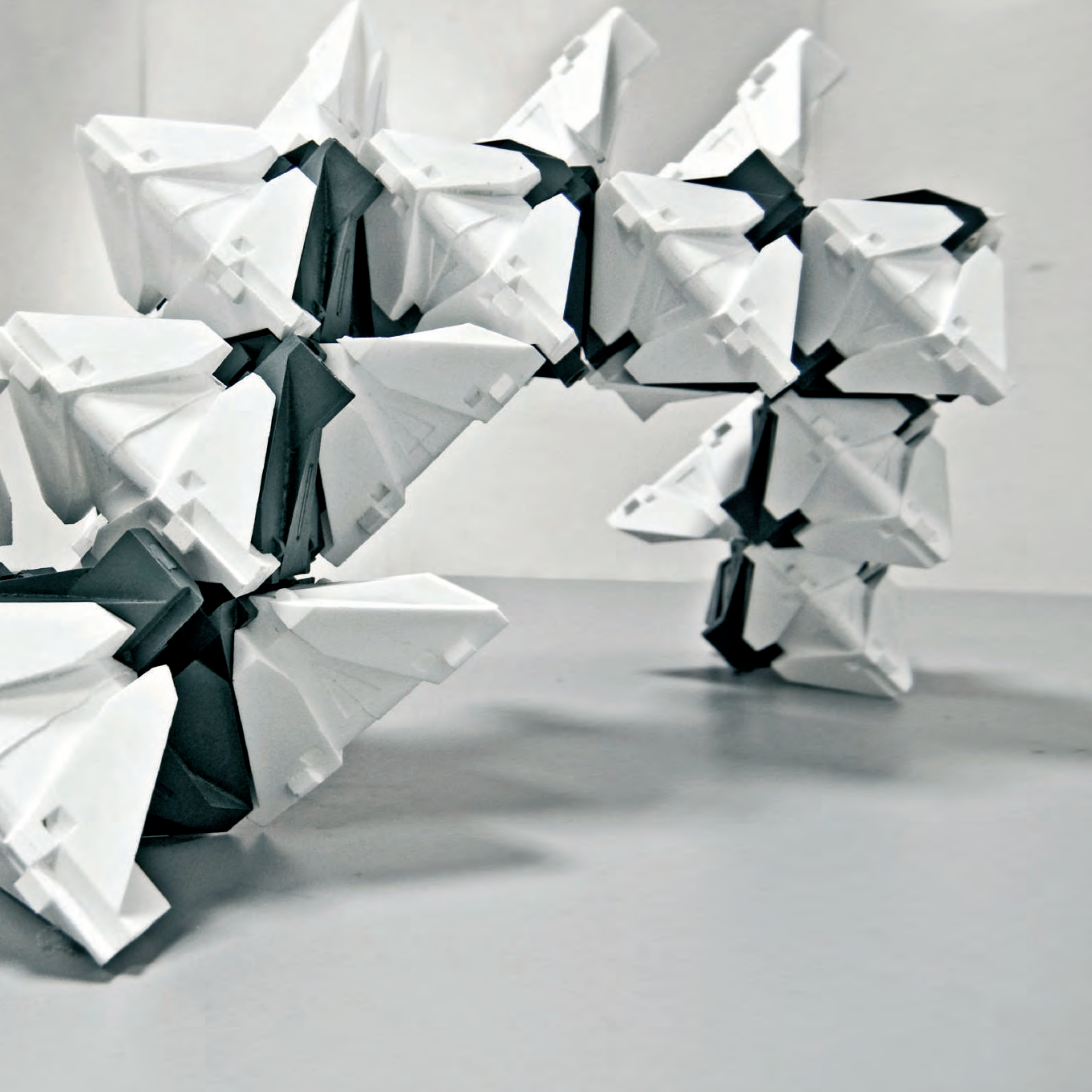

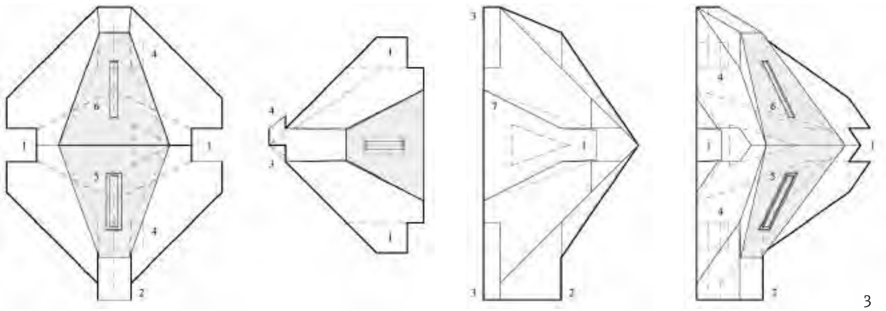

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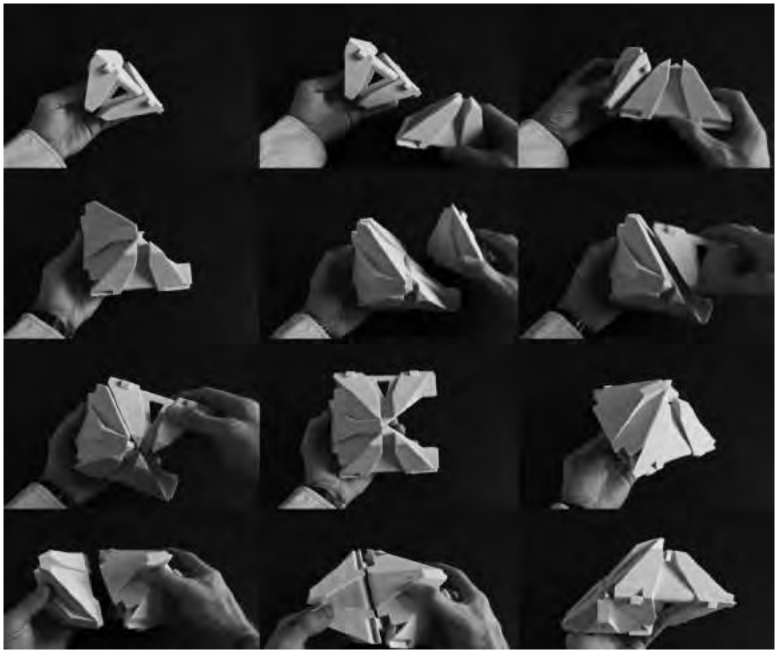

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1: 60-unit working prototype demonstrating 3D single-path and user programmability. White redundant tetrahedrons as input and grey NAND gate tetrahedrons.

2: Four Logic Matter modules demonstrating programmability of base configuration.

3: Female slots to receive (2) male peg 2. Male peg on negative face (5) 3. Half notch to allow positive output and receive male peg (2) 4. Half clip to allow negative output – only when no male pegs (2) exist 5. Negative Face (Output) 6. Positive Face (Output) 7. Input face.

to the complexity of information processing and information transfer from material to material and from assembler (human or machine) to material. A number of techniques have been developed to fight the associated problems with assembly, including precise CNC Machines, robotic arms and large-scale 3D printing, to name a few.

Developments in these fabrication technologies increasingly strive to make larger and more complex machinery to build smaller-than-the-machine parts with imperfect strategies. They fight precision issues with motor/sensor feedback, material tolerances and inevitable machinery fatigue. Before even taking the parts off the assembly line, the machines are fighting accumulating error from imperfect tools, materials, measurements and continuous information. Likewise, assembly teams fight man or machine hours to physically assemble these complex systems with accruing construction tolerances, seemingly approaching intractable problems. All of these systems are fighting an uphill battle, one that is avoiding many of the fundamental issues of assembly. In the near future, if we want to build structures more accurately at extreme scale lengths, we will need to embed discrete assembly information directly into our material parts to self-guide the successful construction of complex structures.

Logic Matter follows in a lineage of research, from the mechanical computing or self-assembly systems of C. Babbage, L.S. Penrose and J. Von Neumann in the 1950s, to the contemporary study of programmable matter, self-reconfigurable robotics and spatial computing by researchers like N. Gershenfeld, S. Griffith, J. Bachrach and E. Demaine. It looks to go further by simply focusing on the communication between our material parts and the people/machines/biology that perform the construction, while eliminating our reliance on electromechanical devices. In our built environment, this stretches from the minute scales of biological machines to the largest of infrastructure. Our building blocks should be engaged in a 1:1 dialogue between themselves and those performing construction. In *Fab: The Coming Revolution on Your Desktop – From Personal Computers to Personal Fabrication*, Neil Gershenfeld frequently notes that the transition from analogue to digital communication can be correlated to the assembly of physical materials; highlighting an opportunity for digital materials to resolve similar problems of noise, error propagation and global inconsistencies that plagued the analogue telecommunications industry. Likewise, our parts should be engaged in a communication of digital logic, ensuring that they are assembled correctly, reducing error propagation, offering storage for long/complex sequences of assembly instructions and providing the means for read-write replication. On the contrary, if we look at the processes of assembly today, from bricklaying to robotic manufacturing, we can see direct comparisons to the uphill battle of analogue communication with error-prone and lossy information/feedback as systems scale. The information that's needed to assemble complex structures today is stored in the human/machine constructor, however, our building blocks of the future should take on that responsibility and directly store assembly information, ensuring accurate, efficient and computable instructions.

Logic Matter is composed of a series of physical building blocks that demonstrate digital logic and computation by passively connecting brick-to-brick (i.e. no electronics, only geometry performs the computation). These building blocks can encode assembly information and guide the user in successfully and quickly building any complex structure. The parts engage in a dialogue with the user, giving information, taking feedback, computing next moves and analysing current conditions. Its parts can be assembled to describe any given geometry (lines, surfaces and volumes) through a linear, chain-like, growth that provides a series of instructions (left, right, up, down) for the user. Further, they implement a digital NAND logic gate to offer a new system of computing with potential for 3D circuit assembly and self-guided-replication.

This system suggests a new paradigm for computing, one that materialises the capabilities of a hard drive and processor from a single sequence of inputs. The building blocks compute on the stored sequences of the previous units, then store and recompute the latest output for the next moves. Logic Matter offers the potential for computing through construction, relinquishing the necessity for global construction information – only local knowledge is necessary at any point during the construction process. Each move can act as a counter, a storage device or an instruction set, informing the user when to stop as well as to ensure a globally accurate construction. This, for example, could ease the repair of complex structures because the material surrounding a hole or fragment would contain the building's blueprint, directly informing a user how to replace missing parts. Similarly, the material storage sequence could be utilised in a form of self-replication where a decoder device could be sent along the sequence of units to replay the sequence of instructions. This system acts as though a building could wear its blueprints as a skin, offering a simple mechanism for duplication, repair or morphogenesis.

Some of the most interesting applications are at extreme scales; i.e. biological machines that have limited computation/storage capacity and thus can rely on the deposited material parts for local assembly instructions, much like the impressive power of our Ribosome to decode RNA into a sequence of folds and create complex proteins. At the other extreme, large-scale structures with upwards of thousands or millions of parts cannot continue to accrue errors, part-by-part. Architectural-scale applications could be built faster, more efficiently and with fewer errors, simply by encoding computation into the material, and therefore, computing the blueprints directly in the walls of our structures. As we dig deeper into the earth or further into space we need to have greater guarantees in assembly accuracy, require less skilled labour and have fewer mistakes or communication issues. The inherent nature of Logic Matter is scale-less because the functioning of the mechanism depends solely on geometry and the interaction with its user; enabling encoded digital assembly for projects large or small.

As a prototype, it demonstrates the programmability of digital logic and user-material communication through an example mechanism. However, in the future, this technique will be further explored through a variety of typologies and will be rigorously tested at extreme scales. This system asks the question: what is computation and what can compute? Once our notion of computation can be expanded to geometry, we can begin to embed computation and digital information into our everyday materials.

Our built environment should be able to self-assemble and store complex sequences of construction information similar to the natural processes of our bodies, processes that combine 10^{23} parts in fractions of a second, efficiently and consistently. Logic Matter is a system that attempts to go one step further in this direction by allowing material computing and material-provided instructions for the user while utilising the power of digital information for guaranteed construction accuracy.

CNCATENARY TOWARDS A DIGITAL FABRICATION METHOD FOR CATENARY SYSTEMS

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THE BARTLETT, UCL

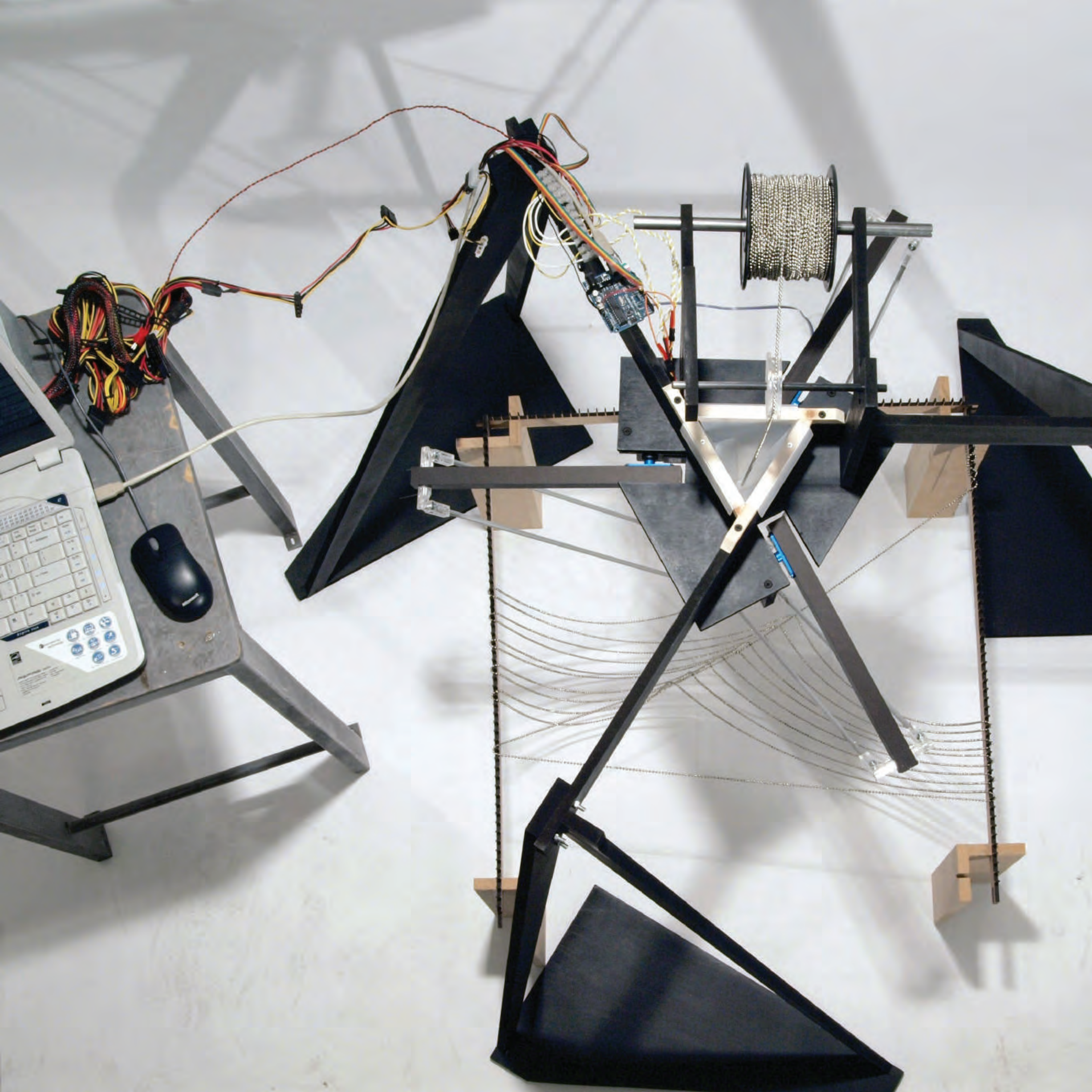
CNCatenary investigates the possibility of developing a digital fabrication process for the production of complex catenary structures directly based on their inherent self-forming properties. Recent research on the adoption of robotics for architectural production has developed new opportunities for the manipulation of conventional material systems. Custom numerically controlled fabrication processes are offering novel and potentially more efficient means for constructing non-standard material assemblies and simultaneously generating sensuous and performative possibilities.

Requiring a forbiddingly laborious process for the application of their form-finding properties, catenary systems have long haunted the imagination of architects. It is suggested that the coupling of a robotic process with the form-finding method of hanging models can yield new and meaningful results concerning the research and fabrication of funicular structures. Developed by Ermis Adamantidis on The Bartlett's MSc Adaptive Architecture and Computation programme, under the supervision of Ruairi Glynn and Marilena Skavara, the work features a series of robotic prototypes designed, constructed and programmed for the manipulation of catenary systems. It constitutes the first generation of machines aiming towards the digital fabrication of catenary systems, addressing the main issues and possible solutions for further research to come.

BACKGROUND AND MOTIVATION

> People who have the ability to create their own tools are limited only by their imaginations in what they can do. Meanwhile, those that are not tool-builders are limited in what they can accomplish not merely by their imaginations, but also by the tools they have available to use.[1]

Increasingly coding has become part of the architect's toolbox, opening novel design processes through the development and customisation of software for specific goals. Adamantidis explores the growing interest within the discipline to develop and customise the functionality of the fabrication tools. CNCatenary explores the possibility of developing a digitally informed process



1: Top view of the robot.

2: Time lapse of the robot while working.

3: Plan and axonometric of the second prototype.

4: Catenary formations using ball chain.

5: A variation of catenaries through the control of the end-effector's speed.

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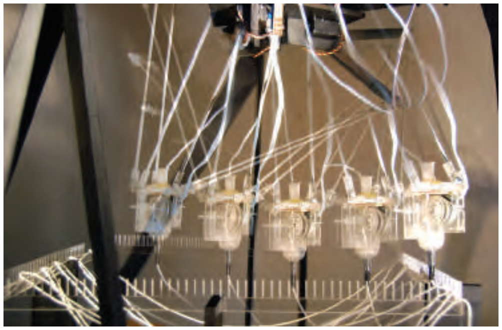

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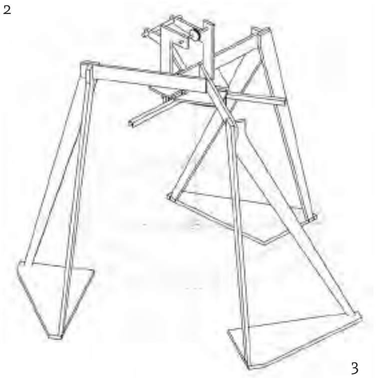

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of fabrication to substitute the conventional way of making catenary models through the devising of a custom digitally controlled machine. This research is set to investigate how 'analogue' aspects of the catenary systems like the material and the physical laws that define their form can be accommodated within a digital process of fabrication.

EXPERIMENTS

The research of CNCatenary is based on a physical experiment that includes the construction and testing of a digital fabrication device. The main objective is the following: to set a robotic process that can produce and manipulate catenary systems with the maximum possible freedom in the manipulation of these systems. A large part of this research constitutes a first iteration that focuses on identifying the key issues and solutions for building such systems and does not represent a final solution but rather conclusions based on a first round of testing.

The design of the prototype for this research is based on the principles of the delta robot – a type of parallel robot used in the industry mainly for 'pick 'n' place' operations. The choice of this robot type is due to the following factors:

· The structure of the delta robot is light and therefore appropriate for the delicate movements it executes, namely, weaving a string on a frame.

· The robotic body extends from a small base that can be fixed above the working surface without being connected to it. This allows for the working frame to be easily reconfigured, moved or replaced and the robot to be demounted and moved as well, without affecting the frame.

· The movements of the end-effector of a delta robot in X, Y and Z directions are sufficiently dexterous and the workspace of the robot can be easily adjusted by the length of its arms.

· A delta robot prototype could be built using servo motors which, compared to the stepper motors needed for a CNC type of machine, are lighter, cheaper and easier to control as they have an integrated feedback mechanism that regulates their orientation.

Two substantial prototypes were built. The first to investigate the kinematics of the delta robot. The second one presented here is fully equipped with the functions and actuators required in order to manage the making of funicular forms. These functions include:

· Moving the end-effector on a straight path between two hooks of the frame.

· Unleashing a string while moving.

· Anchoring the string around a hook.

· Repeating these actions between different hooks of the frame in a continuous process.

· In addition, string can be impregnated with hardening resin in order for the catenary structure to solidify and retain its self-forming configuration.

The robot was developed using a combination of Processing and Arduino platforms. Servo motors were used to drive the three arms of the delta robot and a stepper motor its end-effector. The servo motors were responsible for the X, Y and Z motion and the stepper for dragging and hanging the catenaries from a purpose-built frame of hooks. A range of different kinds of string and ball chains were tested as the material for making the catenaries.

A number of digital and physical parameters were tested in the control of the robot affecting the dimensions of the catenaries and their arrangement on the frame. These included:

· The rotation speed of the stepper motor unleashing the string.

· The speed of the end-effector moving between two hooks.

· The sequence of the hooks that the end-effector travels through.

CONCLUSION

The research focused on introducing the making of self-forming catenary systems into contemporary modes of digital fabrication governed by numerically controlled and robotic devices, in an attempt to emancipate their production from previously prohibitively laborious processes and facilitate new physical experimentations of complex catenary formations. It also has supported a growing body of work by architects to experiment with custom fabrication hardware – just as they do with custom design software – by setting as its main research subject the design and operation of a custom digital fabrication tool.

The lack of previous examples of a similar process has meant that a large amount of the work to date has been problem-solving a technical approach and, through the analysis of early prototypes, identifying the most interesting opportunities for further development. The choice of the delta robot configuration for the design of the fabricating device can be considered successful as it has accommodated the main functions required for catenary production. The full potential of this prototype and its programmed tasks have still to be examined and documented in relation to the different hanging models that they can produce. The development of the prototypes have revealed the major issues that need to be addressed, encouraging further refinement and testing.

UNIKABETON PROTOTYPE

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AARHUS SCHOOL OF ARCHITECTURE

The Unikabeton prototype was developed as the finalisation of the cross-disciplinary research project Unikabeton, which explored the architectural potential in linking the computational process of topology optimisation with the robot fabrication of concrete casting moulds.

The project was developed in cooperation with eight of the largest institutions and corporations within the Danish building industry, including the Aarhus School of Architecture, the University of Southern Denmark and the Danish Institute of Technology. The commission of the Aarhus School of Architecture was to develop a series of optimisation experiments, concluding in the design and optimisation of a full-scale prototype concrete structure.

The investigated process of topology optimisation is a method of structural calculation developed by the Danish mathematician, Martin Bendsøe, using an open definition of problem solving. Prior to the process, an initial volume or design space is modelled, representing a structural component, structural assembly or full

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spatial configuration. The volume is then subdivided into finite elements, and digitally supported and loaded according to standard structural estimations. Executing a topology optimisation from the basis of such a setup, an iterative process of calculation is initiated. Material gradually densifies within the designated volume in the trajectories of the maximum structural stiffness. Simultaneously, material is subtracted from areas outside these trajectories. The process converges towards a theoretical optimum, in which the greatest structural stiffness is obtained with the minimum mass of material, generating a spatial geometry that satisfies this criterion qua its topological layout.

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1: Assembly of polystyrene moulds at the building site, January 5 2010.

2: Detail of 1:10 CNC-milled test mould of prestressed beam in layered medium density fibre boards, May 26 2010.

3: Computer rendering showing the doubly curved 70mm concrete slab with three asymmetrical points of support, September 14 2010.

4: 1:10 Cast plaster model, derived from CNC-milled MDF mould, June 2 2010.

5: Rendering showing bottom-up perspective of the topology-optimised rib structure.

Using this method of computation, the research team at the Aarhus School of Architecture developed a series of optimisation experiments, carrying out structural analysis of results and small-scale simulation of the digital fabrication process. The point of departure for initial experimentation was testing the effect of topology optimisation within a series of simple and well-known structural concrete components in order to generate results comparable to existing technology.

The experiments showed that the optimised structures yielded a 60–70 per cent average in reduction of material usage in comparison to massive equivalents. These reductions are notified in the context of CO_2 emissions generated globally by the production of concrete, which amounts to 5 per cent of the total, global emissions, surpassing the emissions of air traffic by a factor of 2.

Following the initial optimisation experiments of discrete structural components, design and optimisation was undertaken of the Unikabeton prototype structure. Exploring the specificity and versatility of the chosen computational and fabrication methods, a challenging layout was chosen: the optimisation of a non-uniform doubly-curved concrete slab simply supported by three asymmetrically placed concrete columns fixed at the foundations. The design space for the slab was generated using minimal surface form-finding software by establishing two staggered membranes fixed around the planar outlines of the slab and lowered differently at the three columns. Anticipating challenges of reinforcing the optimised structure – methods of the manufacturing and inclusion of reinforcements in the optimisation process still being a question of further research – the bending moments between the columns was reduced prior to optimisation by cantilevering the design space of the slab, thereby minimising the need for reinforcement in the ribs. By increasing the design space depths at the supporting points of the columns, the requirement for reinforcement was further reduced in the top of the slab, generating a structure theoretically capable of sustaining its loads in an unreinforced condition.

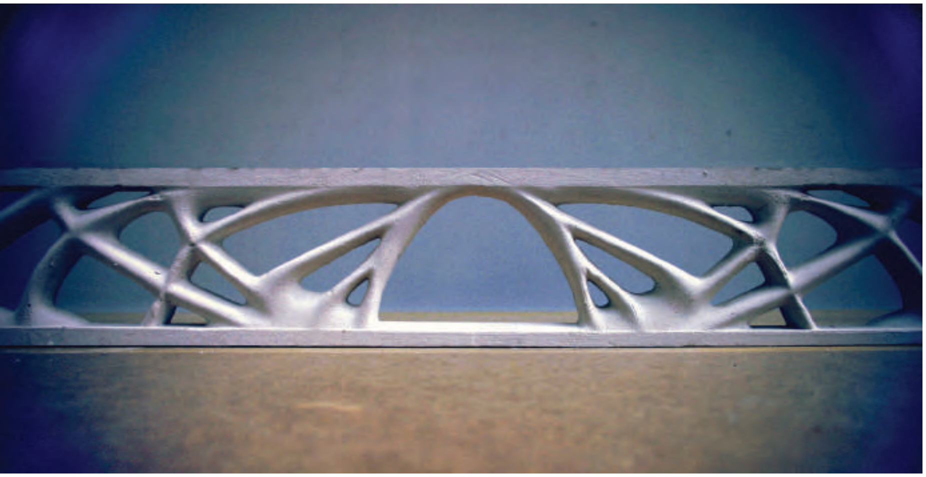
The slab was optimised for an overall uniform load of dead load and snow load, presuming a high-strength concrete. Ensuring that the optimisation output was generated specifically to meet the fabrication requirements of the one-sided CNC milling process, a casting direction constraint was included in the calculation, forcing the topological result to converge towards a castable shape, allowing for one-way mould retraction. The optimisation result was then redrawn and remodelled to prepare the surface for milling.

The optimised rib slab was subsequently analysed and reinforced following the normal engineering codes for strength, stiffness and robustness.

Following a fully digital, 1:1 file-to-factory production process, an inverted negative shape of the redrawn rhino model was directly milled in polystyrene blocks, using the large-scale industrial milling facility at the Danish Institute of Technology. To reduce milling time by an approximate half, a rough milling surface strategy was chosen, forcing the milling machinery to carve out polystyrene at large intervals. Leaving significant traces, the process generates a narrative texture at detail level, accentuating the geometry of the curved structure via the superimposition of a longitudinal cutting pattern on the asymmetrical ribs. The milled polystyrene blocks were assembled at the site using traditional assembly techniques and scaffolding, reinforcement was placed and self-compacting concrete was cast into the formwork.

Representing the first realised, topology optimised concrete structure, the Unikabeton prototype illuminates a number of research perspectives. The technology of topology optimisation is currently applied widely within the aeronautic, automotive and naval industries, primarily for the optimisation of machine part components. Though the body of research elaborated within the present project suggests significant potentials, the application of topology optimisation within the field of architectural design is widely unseen. The Unikabeton project is among the first academic research to address the use of topology optimisation as a constitutive design tool within architectural design of concrete structures.

As a design tool, topology optimisation introduces a significant loss of direct control over form, as the primary generation of geometry is surrendered to the software, growing architectural shapes from levels of information density well beyond the limits of intellectual capacity.



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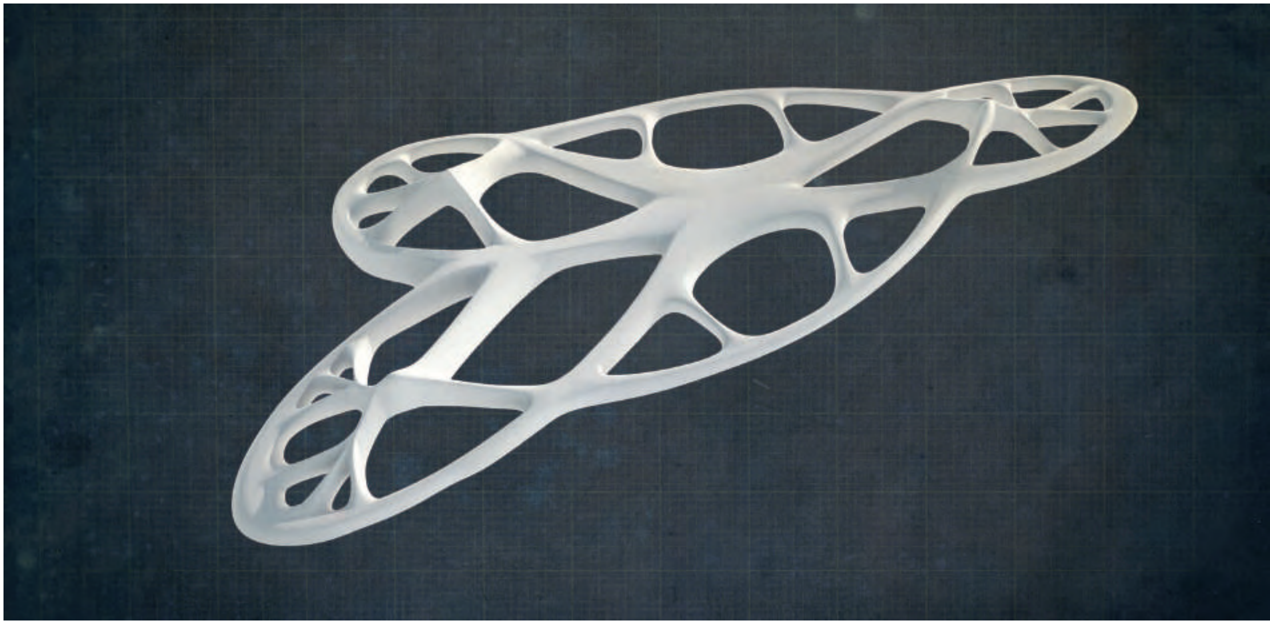

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6: A reassessment of the role of representation occurs within the digital file-to-factory process of realisation, as the drawing models become agents of manufacture. As such, they drive a physical 3D drawing process of the fabrication machinery, leaving an ornament of production traces in the form of tool paths.

7: Finalised optimised prototype structure.

8: Forefront column and rib structure of the finalised prototype.

These circumstances require the architect to formulate new strategies of design intervention, in which domains of control are negotiated between machine and designer. One primary source of such intervention is the formulation of 'non-design spaces'– areas that are included in the static conditions for optimisation, but excepted from the optimisation itself, leaving the areas untouched by the form-finding process. In the Unikabeton prototype, such zones were designated to the top concrete membrane and the three columns, in order to accommodate project design requirements, such as leaving a non-perforated top surface for weather protection.

The optimisation results emerge within a particular morphological language of form specific to the computational logic. These structural shapes can be seen as a direct expression of the inherent static forces of the system, with formal resemblance to the morphology of biological structural systems, with which they share a principle of maximum structural performance generated by the smallest possible mass. While the project setting for Unikabeton allowed for an exploration of this emerging

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architectural morphology, by facilitating a relatively direct translation of the results into buildable shapes via the CNC-technology, optimisation results could also be simplified and realised with less sophisticated production machinery. Such simplifications would require a geometrical interpretation, reducing to a certain degree the structural efficiency of the form, thus enabling a negotiation of efficiency over realisability and cost. In this perspective, topology optimisation can be viewed not only as a facilitator of novel tectonic languages but also as a pragmatic tool for generating intimate form-structure relationships within processes of architectural design, relating to already established formal traditions of industrially build architecture.

Revealing the trajectories of the static forces to the observer within the build shape, the subtraction of superfluous material simultaneously offers significant reductions in the environmental cost related to the production of the structure, in terms of the energy saved by the minimised need for concrete production and transportation. As the polystyrene used to create the formwork can be recycled and reused for new formwork after use – and the fabrication of it requires only a fraction of the energy consumed by concrete cement production – the environmental savings generated by the optimisation are only marginally affected by the polystyrene consumption within the fabrication process.

While this production method provides an accessible and affordable early strategy of realisation – scalable to industrial standards due to the relative inexpensiveness and lightweight of polystyrene that enables easy transportation and on-site assembly – a number of promising alternatives and replacement technologies are being explored. While applicable in the context of in-situ casting construction work, polystyrene downcycles through repeated reuse due to the epoxy and oil coatings applied to the mould surfaces as parting agents. For prefabrication production lines, where moulds need not be transported and assembled at a building site, heavier and more fragile mould materials – such as casting sand and hard wax – was explored within the project, allowing for continuous reuse without a gradual downgrading. Other technologies, such as pin bed and actuator controlled moulds, could potentially replace the time-consuming milling process and subtraction of mould material, while even more advanced alternatives, such as the D-Shape large-scale concrete rapid prototyping device, proposed by Italian engineer, Enrico Dini, suggest that even free-form manufacturing processes can be liberated from the overall need of formwork fabrication.

In the conceptualisation of spatial structures, topology optimisation allows for the generation of results that fall outside known categorisation. While non-computational structural design implies an empirical process of form development, drawing on the historically accumulated experience with architectural typologies, topology optimisation enables a shift from typological to topological design thinking, in which the need for empirical experience is exchanged with the need for a generic knowledge of the prerequisites of optimisation. As noted by Japanese engineer, Mutsuro Sasaki, this shift facilitates the emergence of new types of structures – flux or hybrid structures, in which all structural components are synthesised into a continuous whole, negating sub-classifications of the system into conventional constituent parts such as beams, slabs and columns. Parallel to this, the methods allow for a re-evaluation of well known structural problems, holding promises of notable innovations within known structural systems.

For further investigation, a number of key research questions remain: the optimisation and manufacturing of reinforcement provides a practical challenge in design of topology optimised concrete structures. While awaiting the fruition of ongoing development of computational methods for optimisation of composite material design spaces (steel and concrete), strategies for the inclusion of pre-stressing cables within the optimisation process were, with some success, explored during the project. Similarly, efficient strategies for the manufacturing and positioning of reinforcement in the complex formwork need development for complete solutions. In the Unikabeton prototype, the necessary rebars and stirrups were formed by hand, which is both uneconomical and labour-intensive. A number of alternatives candidate for further investigation, such as replacing the steel bars with flexible glassfibre cables, or shaping the steel bars by CNC-machinery, fed by correlated digital models.

On the level of design theory, the new distribution of roles between machine and designer calls for the development of a new set of design methodologies, supporting also the resonance of architectural intents that evade numerical definition. On the background of such, a reassessment of the interface between calculus and fabrication could facilitate the exploration of a novel vocabulary of tectonic morphologies.

SCANLAB

WILLIAM TROSSELL & MATTHEW SHAW,
THE BARTLETT, UCL

ScanLAB is an ongoing series of experimental projects investigating the use of large- and small-scale 3D laser scanning in architecture. The projects focus on the role scanning plays as a design tool, as a method of representation and as a catalyst for design speculation. This article questions scanning's current role in design and fabrication and, through examples, suggests its potential future. ScanLAB explores 3D scanning at all scales, from small and intricately detailed object capture to highly accurate terrestrial scanning of forests and cityscapes. The technologies employed range from state-of-the-art LiDAR based surveying tools to desktop self-assemblages. The projects explore tools at the cutting edge of fabrication technology and those that, through open source software and a trip to a local hardware shop, are already available to us all.

DESIGN AND FABRICATION

3D scanning has been employed in the manufacturing industry for a number of years for quality control and monitoring purposes. It acts as a tool for checking the actual product against idealised digital designs. It also plays a vital role in reverse engineering for

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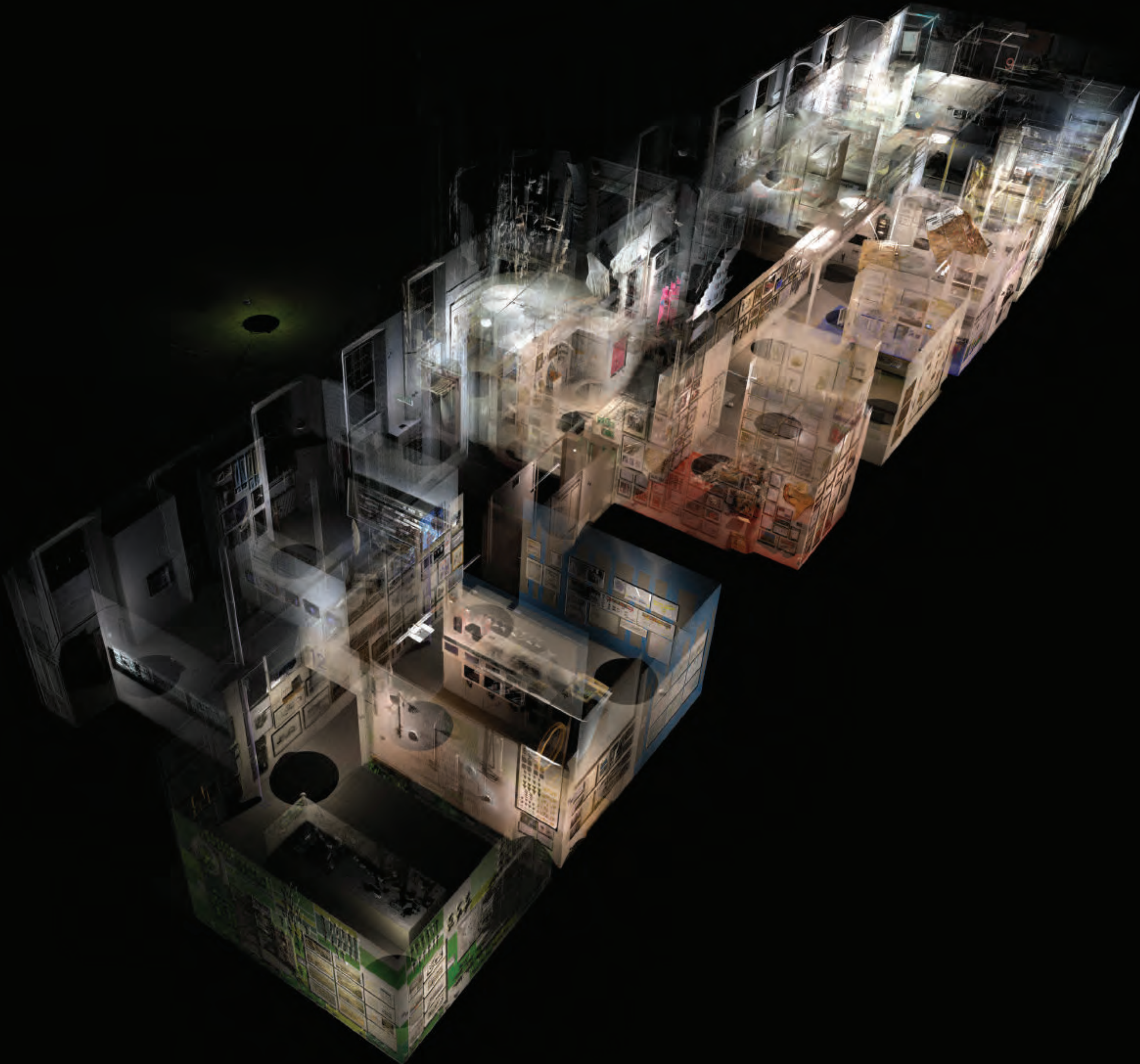

1: Terrestial scan of '55/02' at Kielder Forest and Water Park by sixteen*(makers). The painted steel shelter was pre-fabricated by Stalbogen GmbH in Blankenburg Germany.

2: The Bartlett Summer Show 2010 – perspective View.

out-of-production parts, recreating components from recent and ancient history. These are scanned, 'tidied' in CAD software and then prepared for digital manufacturing techniques. A number of ScanLAB projects have used 3D scanning for bespoke component manufacture, enabling and merging digital and analogue production techniques. The following case studies highlight the direct link between digital and analogue making enabled through the use of 3D scanning.

STEALTH TOOLS

This series of works uses scanning in two ways: to synchronise a digital and a physical workflow, so objects could be manipulated both by hand and by computer software, and then to test the success of the final 'stealth objects'. These stealth objects are the tools of a hypothetical insurgency, aiming to go undetected by escalating 3D scanning surveillance techniques. Initial 3D sketch pieces were intuitively carved from Obeche then scanned using a self-built 3D scanner and open-source scanning software. The digital artefact captures the original form, including precise notes, comments and instructions from the surface of the originals.

These sketches guide the creation of CAD-modelled additions and insertions, they act as digital post-it notes from the traditional craftsman to the digital designer. In this example the original wooden form has SLS nylon grafts applied to its surface before a silicone mould is taken for a final translucent rubber cast. In a further example, the original wooden form is scanned, replicated in CAD software then machined from black plastic using a three-axis CNC machine. The final gloss black object and translucent cast are then re-scanned to test their 'invisibility' to the scanning process that created them.

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ENVIRONMENTAL CAPACITORS

This project sets out to investigate the use of terrestrial LiDAR to form the basis for a detailed environmental analysis of a site. A pocket of Kielder Forest, previously flattened by a storm, was scanned to create a digital landscape in which prototypes and weather conditions could be formed, honed and tested. The scans of the site identified potential areas and microclimates in which the installation could operate and, with an acutely accurate representation of the site, parts could be manufactured to fit perfectly. Tree attachments mimic the form of their hosts and are designed to provide an open framework that the tree could grow and consume over time.

REPRESENTATION

Highly accurate, fast capture of colour 3D data at a range of up to 150 metres has vast potential to record and to represent existing, proposed and past architecture. This data can then be presented not only from the point of view of the camera/scanner but from any other viewpoint around or within the navigable dataset. It can provide a range of information, from simple survey data to complex 3D details, precisely located in a global spatial system. Current uses include restoration of sensitive historical sights and surveillance of remote and dangerous sites, such as the interior of nuclear reactors.

The following case studies exemplify scan data as a method of describing transient architectures. The method of capture and presentation is presented as both emotive and yet forensic in its accuracy.

THE BARTLETT SUMMER SHOW, 2010

The Bartlett Summer Show is a collection of more than 1,000 models, installations, prototypes, drawings, photographs, films, sketches and designs presented across four large exhibition spaces in the Slade School of Art each summer. The show lasts for just seven days but represents the annual output of more than 450 Bartlett students, thousands of hours of labour and thousands of pounds in materials.

In 2010, 48 hours of scanning produced 64 scans of the entire exhibition space. These have been compiled to form a complete 3D replica of the temporary show, which has been distilled into a navigable animation and a series of 'standard' architectural drawings. What is usually such a 3D, sensual and temporary experience is abstracted into a series of precisely detailed snap shots in time. The work becomes a confused collage of hours of delicately created lines and forms set within a feature prefect representation of the exhibition space. Sometimes a model or image stands out as identifiable, more often a sketch merges into a model and an exhibition stand, creating a blurred hybrid of designs and authors. These drawings represent the closest record to an, as built, drawing set for the entire exhibition and an 'as was' representation of The Bartlett's year.

SLOW BECOMING DELIGHTFUL

'Slow Becoming Delightful' was an installation in the Kielder Forest designed to draw attention to the magical properties of weather events. The installation consisted of a series of passively activated pressure vessels linked to an array of humidity tanks. Over time energy and water was collected and stored and, when the 'ideal' circumstances were in place, a fine mist was dispersed creating a rainbow.

The installation is an ephemeral moment. Using the scan as an almanac, sun path studies predict potential territories and times in which the installation could operate. This was then visualised by placing designed elements back in amongst pointcloud data to produce a series of drawings which amalgamate digital and real. The sub-millimetre resolution of terrestrial laser scanning is capable of uncovering previously hidden site details and conditions. This unparalleled level of site information can then be fed into traditional workflows to create propositions capable of exploring and exploiting these extremes in tolerances.

SPECULATION

The potential for collection and distribution of highly accurate spatial data of all major urban areas globally is a real possibility for the near future. It is believed that the vehicles used by Google to collect information for Street View are also equipped with mobile LiDAR units. These collect helical sets of pointcloud data in rings as the vehicle travels down a street, essentially taking a perfect street section every few millimetres. Each of these sections is located in global terms using the vehicles GPS and inclinometer. Much of this data may have already been collected for majors cities across the UK. It is believed that issues of privacy and personal rights are the greatest barrier to Google's use of such information, rather than issues of data collection and handling.

With Google tourism acting as many people's preferred method of urban spatial research and with Second Life proving the financial and social captivation of digital worlds, 3D scanning is likely to be a major tool in the creation of future versions of our cities and our world. The following works explore the potential for error and subversion within the scanning process and its future mass publication.

SUBVERTING THE LIDAR LANDSCAPE

This series of works explore the possible subversion of future city scale 3D scanning. A series of hypothetical devices are installed across the city which edit the way the city is scanned and recorded. These tools are not digital hacks but physical interventions. They manipulate the scanning process as it happens and act as waypoints and markers linking the physical world to the digital. Tools include the 'stealth drill', which dissolves scan data in the surrounding area, creating voids and new openings in the scanned urban landscape, and 'boundary miscommunication devices', which offset, repeat, relocate and invent spatial data such as paths, boundaries, tunnels and walls.

SURFACE ERROR

This series compounds the slight errors implicit in the scanning process and shows the distortion, mistruth and beauty that repeated errors can create. A base SLS-printed

3: Combined digital design and terrestrial based LiDAR scan.

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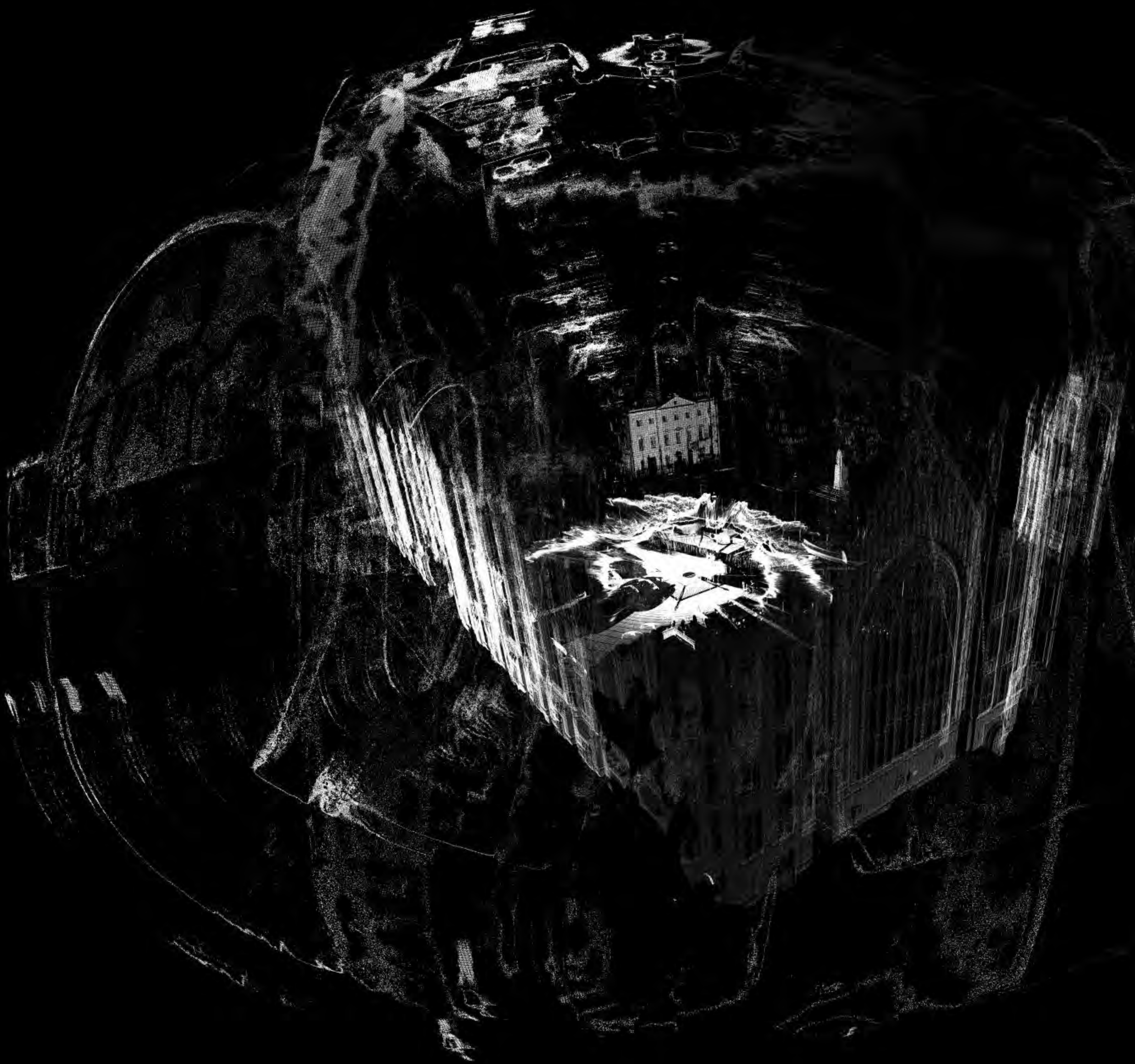

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4: Plan/section/perspective from a subverted terrestrial laser scan of Parliament, Westminster, London, 23.56 hours, 17.06.2010.

5: Scan degradation, target 3, original and fifteenth generation.

target is repeatedly scanned, 3D printed and re-scanned for 15 iterations. This micro test of distortion could be applied on a city scale, altering its digital appearance.

CONCLUSION

This paper suggests that 3D scanning has the potential to fulfil the role both of enabler and muse to architectures of the future. The combination of 3D scanning and digital manufacture provides an immediate and direct link between the traditional maker and the digital designer. Contemporary designers increasingly straddle this divide and the physical feedback that scanning and rapid fabrication provide is a vital new tool in the box.

As a method of representation scan data has a unique ability to capture architecture in time. The cloud of data collected can then be curated at a later point, but the facts of the moment remain. This paper suggests 3D scanning can be both an emotive conveyer of architectural ideas and can provide the closest 'as built' or 'as is' drawing set for any completed project.

As such, an emerging technology scanning is ordinarily performed with the distinct aim of precise data collection. This paper suggests that with such pioneering tools the capacity for speculation and experimentation are equally as likely to aid design, to provoke moments of delight and provide commentary on potential architectures of the future.

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FREE-FORM METAL INFLATION & THE PERSISTENT MODEL

PHIL AYRES,
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The Persistent Model proposes a design strategy that couples representation and artefact in a circular relationship as a means of managing indeterminacy throughout the various phases of architectural activity, namely: design/fabrication/construction and occupancy/use. The proposition maintains the instrumental capacity of representation as a space of speculation and specification, whilst attempting to temper its ideal, predictive and pre-determined status in the tension between the making-of-information and the making-of-things. Addressing these attributes of representation is deemed necessary because architectural artefacts tend to reside in (and even within themselves, construct) contexts that tend towards the endemically dynamic and contingent.

Free-form metal inflation provides a conceptually congruent material veil to these concerns. This fabrication procedure is a derivative of hydroforming, but it differs in that no die is employed against which to inform the sheet material. Rather, two sheets of steel are welded at the seam to form a sealed cushion into which a fluid medium is introduced. This material organisation inflates as the internal pressure increases, pushing the material beyond its elastic limit and into the phase of plastic deformation. The substantial tooling cost for the die is therefore eradicated, but so too is the die's influence on the production of repeatable and accurately predictable results. Outcomes will therefore deviate from the initialising representations (used to laser-cut the flat sheets of the cushion) with greater or lesser degrees of predictability. The results are a witness to a sensitive dependency established between material behaviour and the nature of the imposed geometry.

The simplicity of the forming process belies a complex matrix of interactions occurring within and between a variety of microstructures (atomic lattice and grains) and macrostructures (component organisation as a composite of two sheets and the geometric profile of the composite). As these interactions are driven through the inflation process, dramatic transforms occur to the component's formal and performance attributes resulting largely from permanent (plastic) buckling. Within a design context, the overriding concern with this method of fabrication revolves around the issue

1: Persistent Model #1: the unanticipated artefact.

2: Starting configuration. Persistent Model #1 fully assembled and prior to inflation. The starting configuration was conceived as a layered stacking of 2D planes or 'drawings' awaiting deployment.

3: Constructing constraint contexts. In-situ sequential inflation constructs sensitive constraint contexts for the inflation of subsequent components.

4: Detail of the connection between discreet components to construct an aggregate. Connection points were located within zones of high deformation in order to amplify the potentials of spatial transform.

5: Inflation simulation. Attempts at simulation met with limited success. The lack of correlation between representation and physical artefact is compounded as aggregates are investigated. This disparity is seen as an opportunity for the proposition of the Persistent Model that operates through error-controlled regulation. Digital inflation studies by Anders Holden Deleuran, CITA.

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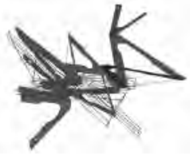

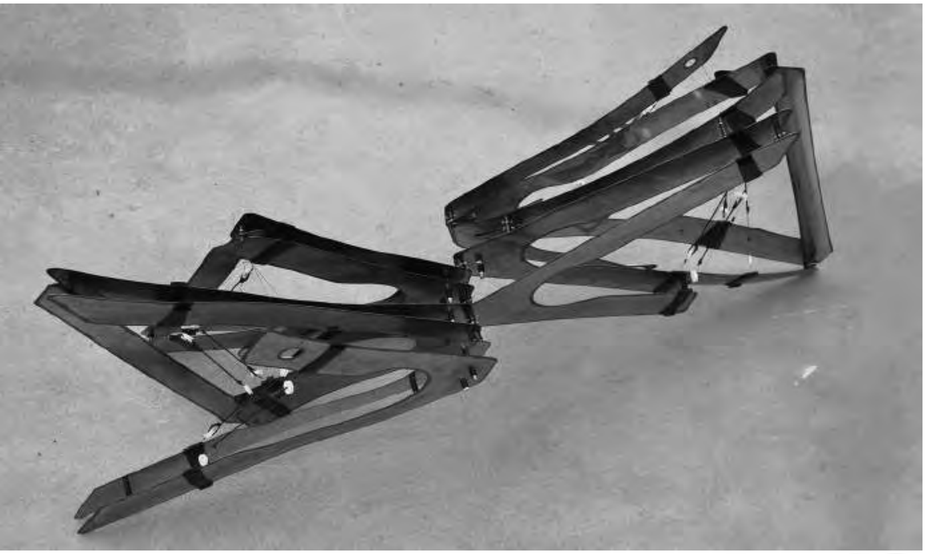

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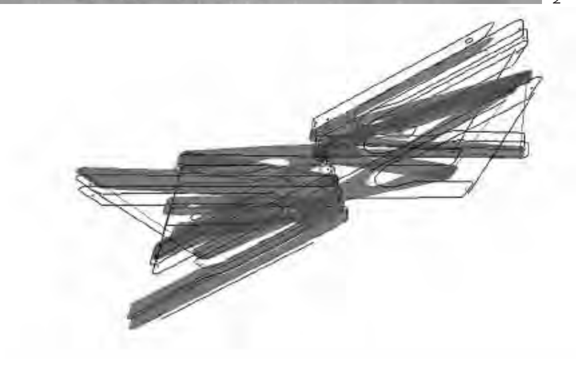

of accurately representing the significant and often unpredictable contribution to artefact attributes. However, our currently employed methods of computer-based simulation of the inflation process are not able to accurately predict these and do not model buckling formation. Clearly, these inaccuracies at the component level are only compounded when considering aggregates.

The first series of explorations documented in the illustrations presented here have shown the development of certain predictable yield lines relative to particular geometrical features of the cushion profile – see, for example, those occurring around internal radii in the chevron and bar components. This points to the next phase of the research, which will empirically and systematically investigate the relation between geometric features and the formation of predictable yield lines. A set of 'primitives' are currently being fabricated for testing.

However, in addition to the predictable yield lines there is often unpredictable buckling that occurs within individual components, particularly as the profile geometry becomes more complex. Assuming for a moment that the complexity of the profile is of value, the concern then becomes one of determining the locations of unpredictable yield line formation. This poses a formidable, if not possibly futile, computer modelling exercise if it were to be conducted in advance.

A resolution to this might be considered by shifting the underlying concerns of representation from anticipation to feedback. This is a central characteristic of the Persistent Model, which attempts to provide a design space in which the anticipatory is tempered through active feedback.

Feedback defines a responsive relation of a system to change. This allows the system to measure the extent of deviation between goal and current state before deciding upon a course of action. The system regulates by controlling error. By definition this is not ideal, however, the payoff is that determined actions are more fully informed.

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The proposition of the Persistent Model provides a compelling alternative to the linear relationship that generally binds design to construction to occupancy and use, by suggesting the coupling of representation and artefact through feedback. The implications of such a proposition are extensive, laying the ground for architectures of sensitive active response and adaptation. In relation to the free-form inflation studies, this framework provides resources for understanding how to manage the unpredictable deviation exhibited between initialising representation and the physical outcome of components. This in turn points to defining a role for the digital in managing the unpredictable component of the dynamic physical phenomena.

Persistent Model #1 considers the site of indeterminacy as the fabric of the construct itself. This is promoted by aggregating components together in such a way that local transforms impact upon the whole. In addition, the inflation method permits arbitrary arresting and resumption of inflation, which suggests potentials for material transforms to be driven in response to demand, but also compounds the inability to anticipate results by constructing constraint contexts – local zones of resistance that impact upon subsequent inflations in various ways such as forcing components into premature buckling.

Through the inflation period, pressure readings informed a significantly simplified digital model that recorded very coarse spatial transforms between the components. The principle aim was to establish the real-time line of communication between artefact and representation and test intensive and extensive methods of sensing. Clearly the model is currently inadequate in anticipating the predictable – and being informed by the unpredictable – buckling behaviour, but this provides a clear avenue of future investigation that will be partly informed through the planned systematic testing outlined earlier.

One of the principle implications of this work is the questioning of the established demarcations between design/fabrication/construction and occupancy/use that occurs by considering methods of fabrication that extend into the life-cycle of the artefact, continually transforming it. The notion of the Persistent Model offers a design space through which such a proposition can be supported. However, the immediate task at hand is to develop a greater understanding of the material behaviours involved in the fabrication process of free-form metal inflation, to learn how to represent and steer these, and establish their design criteria.

MATTER & MAKING

FABLAB, TAUBMAN COLLEGE OF ARCHITECTURE & URBAN PLANNING, UNIVERSITY OF MICHIGAN

The following three, independently authored, works share a uniquely common thread. They were all fabricated using custom-built robotic fabrication equipment at the Taubman College of Architecture and Urban Planning, University of Michigan. Further, these projects share the ambition to saturate the design process with feedback from the behavioural logics of matter and making.

Robotic fabrication is an alliance between generic equipment and custom processes; robots were arguably the first truly open-source fabrication tools. The machines themselves, in this case a seven-axis industrial model, are relatively generic and, while continually improving in performance, they are clearly linked to their 50-year-old ancestor, the Unimate.[1] The promise of robotic fabrication has always been the ability to perform a multitude of unique tasks from a common programming platform; while specific manufacturers use unique syntax, the offline programming techniques used are consistent. The change in recent years has been contextual, a result of the development of computational design processes by innovative architecture practices and educational institutions. The use of algorithms to directly control fabrication tools is a natural progression; it simply requires an understanding of the specific fabrication process and the ability to simulate the kinematics of the machine tool.

Taken together these projects demonstrate the fallacy of the digital/analogue dichotomy, freely and simultaneously traversing material and computational substrates. Each project treats matter as an intelligent collaborator in the creative process. Empirical metrics (plastic versus elastic deformation, foam vaporisation rates, etc.) and aspects of the production process, including machine tool simulation, are computed and reintegrated into form-generating and/or control algorithms, creating a feedback loop between material and digital computation. In Bent, the arm is used to bend thin wall tubing, through a custom gripper/forming tool. The wavePavilion uses the robot to both tend and control a custom-fabricated rod bender as an external axis. For Periscope Tower the arm is fitted with a hot-wire cutting end-effector, carving ruled geometries from EPS foam block. The robotic fabrication research taking place at the University of Michigan is not limited to these techniques alone. Traditional subtractive

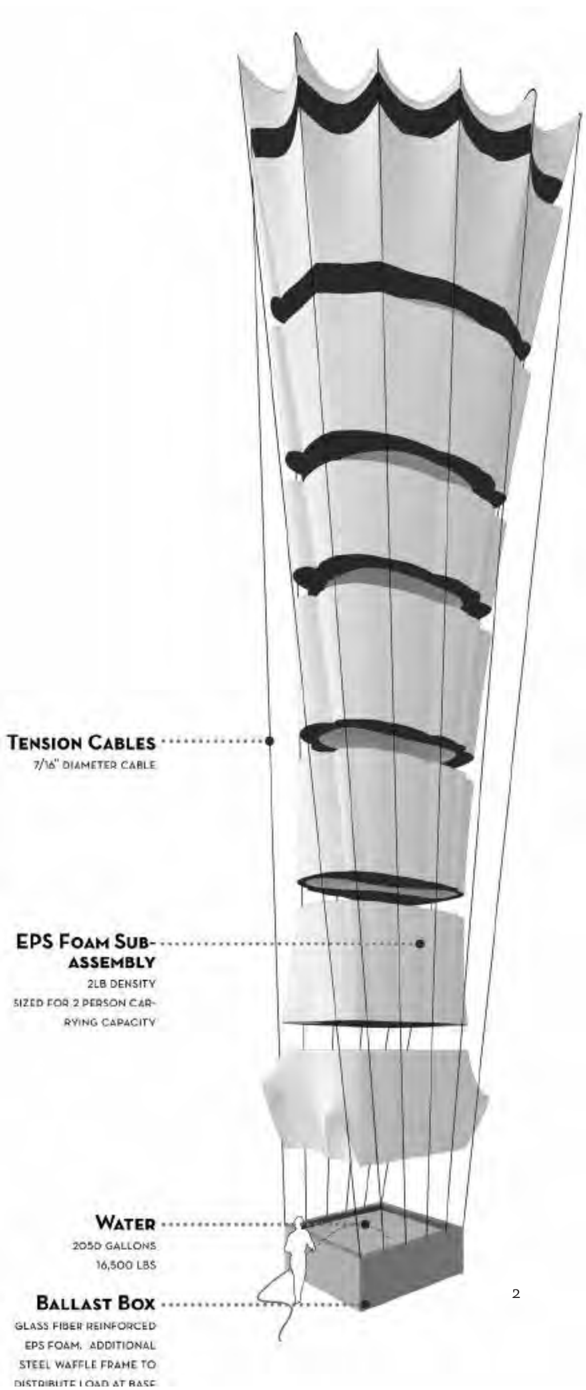
processes, such as milling and abrasive water jet cutting are being extended to leverage additional degrees of freedom. More experimental processes such as large scale additive fabrication, using rapidly curing two-part foam, have been developed to build large complex-curvature self-supporting formwork components without the material waste associated with purely milled forms.

While many, if not all, of these processes have existed in industry for many years, the productive impact of their specific set of possibilities and resistances on architecture remains an exciting and contested territory. What is significant is not the value of a particular machine, in this case an industrial robot, or of any specific fabrication technique. Rather it is the move away from static object-centric models, with neutral or deterministic relationships to material, towards operative models where a given project's physics – its way of materially entering and occupying the world – is *intrinsic* to the design process. The latent argument behind the fabrication research conducted at the University of Michigan is that the phrase 'file-to-factory' must not be a reductive celebration of expediency but instead a perpetual challenge to increase the number and quality of feedback connections between design, matter and making.

PERISCOPE FOAM TOWER
BRANDON CLIFFORD & WES MCGEE

Periscope is the winning entry in the 10Up! National Architecture Competition: an experiment derived from Matter Design's ongoing preoccupation with volume. The 10Up! competition brief was an exercise in constraint. It called for entries that could be constructed by a two-person team, working with a $5,000 budget. The team would be given a month to design an installation for a 10-ft-sq. plot, which could be installed in less than 24 hours. Mounted in only six hours, Periscope is not only a beacon for the Modern Atlanta Event, but is also a product of contemporary digital fabrication culture in that the means and methods of fabrication were developed in parallel to the design, namely custom robotic fabrication tools. The regulations did not stipulate a height restriction and most entries assumed the 10-cubic-ft volume. Periscope, at 50 ft tall, was more ambitious.

From a distance, the observer confronts the sheer magnitude of the figure. The tower appears as tensile fabric stretched vertically by impossibly thin compression rods. This initial confusion is



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1: Assembly of Periscope: Foam Tower.

2: Assembly diagram.

3: Custom Robotic hot-wire cutter.

productive: it pulls the observer in for closer inspection to reveal Periscope's logic of rough stereotomic construction. Two portholes at ground level invite the spectator to peer up the 'skirt' and through the body of the tower. This isolated view crops a view of the sky and reveals a new internal figure that is not coincident with the exterior surface. Rather, it is a figure created by the intersection of two conical views, a result of a solid boolean, not surface, offset. Persicope resists an initial reading of its form as a surface membrane. Where the eye once read tensile fabric there is now solid compressive foam. The compressive rods are actually tensile cables.

This rhetorical inversion is both a commentary on the contemporary practice of surface operation (as opposed to volume) as well as a vehicle to pull spectators in –ultimately to the Modern Atlanta Event. The tower was fabricated using a custom-built, seven-axis robot-controlled hot-wire cutter at the University of Michigan's Taubman College of Architecture and Urban Planning. Over 500 custom foam units are carved from stock blocks of EPS (expanded polystyrene) foam. These blocks are then stacked in a running bond and assembled into 3-ft-tall sub-assemblies. At the top and bottom of each of these sub-assemblies is a plywood profile performing as both shipping protection and, more importantly, as a jig to ensure the manual aggregation of units would not drift away from its intended geometry. The stacking of units is a manual process. Attempting to align irregular units results in subtle variations between each course. While these misalignments emphasise the stacked logic, further precision could be achieved with a jig at each coarse, indexing rods or locking geometry connections. In addition to these manual misalignments, a small error tolerance is needed with such a long hot-wire cutter as the slack of the length can cause drifting. More robust fixturing methods for the foam would also reduce these errors.

Each sub-assembly was designed to be light enough for two people to easily carry. When stacked three high, each would fit snugly inside a semi-trailer. Fourteen sub-assemblies stack to construct the 50-ft-tall figure held down with tension cables to the ballast base. This ballast weighs approximately 16,500 lb in order to resist the overturning forces of the design wind.[2] The interior and exterior surface of the volume kiss at a minimum of 4 in. in the centre of the tower, but are free to expand and depart from each other to serve their individual purposes resolved with a poché of foam. This technique, as well as the material properties, questions the notion that contemporary architecture must perform in the realm of paper-thin surface.

In recent years, the digitally fabricated installation boom has empowered architects. By directly engaging the making process the architect is able to regain control over fabrication methods that were once the sole province of the construction industry. Unfortunately, industrialised construction materials have been compressed into economically friendly paper-thin sheet materials. Composite woods are covered in luxurious veneers, walls are reduced to 6 in. of depth, stone construction is typically wafer-thin cladding on a CMU wall. This economy-driven industry has good intentions, providing better building materials at an efficient price. These well-intentioned innovations have also had a parallel effect on architecture, causing the collapse of depth via materials and methods, as well as encouraging the tendency towards understanding the interior and exterior as isomorphic. Left with a catalogue of sheet materials, contemporary digital fabrication methods have produced a plethora of folded/notched/bent/perforated-pattern/surface-deep projects. Matter Design has previously engaged the topic of volume in such projects as A Change of State,[3] the Drawn Dress[4] and AtmoSPHERE.[5] All these projects address volumetric occupation, but with thin material. In order to engage a broader reading of volume, one must advocate for a solid material with girth, while also competing with the fiscally efficient sheet materials.

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A number of volumetric materials have the potential to fulfill this research agenda: AAC (Autoclaved Aerated Concrete), Reconstituted Stone and EPS foam.[6] Matter Design selected EPS foam as a volumetric and inexpensive case study material for the Periscope tower. After all, it is 98 per cent air by volume, making it around one dollar per cubic foot. Perhaps this is why foam is typically relegated to fill material. The Federal Highway Administration currently uses large blocks as earth-fill (EPS is inert when buried) under highways. By this example, it is literally cheaper than dirt. EPS also contains no CFCs and is 100 per cent recyclable. Manufacturers return to pick up scraps from the fabrication process to toss back into their next batch free of cost. Transportation by land can be an issue, since volume matters over weight. Whether one is shipping stones or balloons, the cost per volume is the same – making a truck full of foam inherently inefficient. This very restriction is why EPS foam manufacturers are widely and regularly dispersed, making local sourcing accessible. Of course this only helps as long as the fabrication facilities[7] are also equipped for the methods of making. The material properties of EPS foam, in conjunction with advanced fabrication methods, provide a solid platform to revert back to stereotomic[8] construction logic.

Most contemporary digital fabrication techniques are developed and informed by sheet materials. CNC (computer numerically controlled) milling a custom profile is no longer an innovative proposal. Milling a solid figure out of a block at the scale of a tower is cost- (and time-)prohibitive, and casting produces volumetric but regular components. In order to appropriately address the issue of volumetric fabrication, one is required to research the methods practised when working with volume was common practice. We at Matter Design translated the developed surface[9] technique into a digitised process as a way of embracing the somewhat lost practice of stereotomy. The developed surface (while ironically re-appropriated to the more widely known 'developable surface' that holds its roots in surface-thin materials) was a method for customising stone carving through the minimal means of a sweeping line that can be flattened or from a 3D geometry into a 2D drawing, otherwise known as a trait.[10] By extracting this principle, it is possible to conceive of this hypothetical line as a physical and CNC device – a custom robot controlled 4-ft-long hot-wire. This converging of past techniques with contemporary materials and methods informed reciprocity between drawing and making.

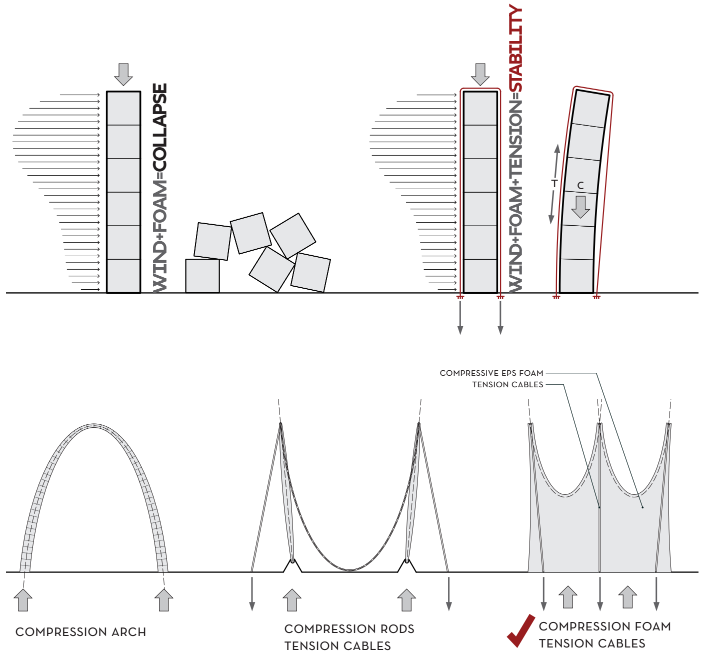
Stereotomic construction is inherently a compression-based system as its material is stone – a very heavy

4: Pre-assembly process.

5: The bottom half of the tower is built from the bottom up, while the top half is built from the top down. The top half is then lifted by the crane on to the bottom half and strapped down with the cables at the base.

6: A crane is required to aggregate higher than the first three sub-assemblies. A person is still required to rappel with the unit in order to assemble.

7: Explanatory diagram of tension cable and foam compression structure.



RHETORICAL STRUCTURE

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material. Foam, on the other hand, is without significant self-weight. Ironically the impetus to engage the process of stereotomy conflicts with the prompt for a temporary installation. In designing this tower, tension is required, but the research agenda is not limited to lightweight materials. Today a majority of compression-structure research is occupied by thin-shell research utilising form-finding techniques. When considering advanced techniques of custom carving solid blocks of material to variable depth dimensions, one can envision compression-only structures that are not dedicated to structurally determined forms. By varying the sectional depth with volumetric materials, a method of 'depth-finding' as opposed to 'form-finding' could emerge. Further applications of these methods with materials of self-weight will position contemporary architecture with the knowledge to undermine the well-intentioned construction industry and re-empower the discourse with the old and now new tool – volume.

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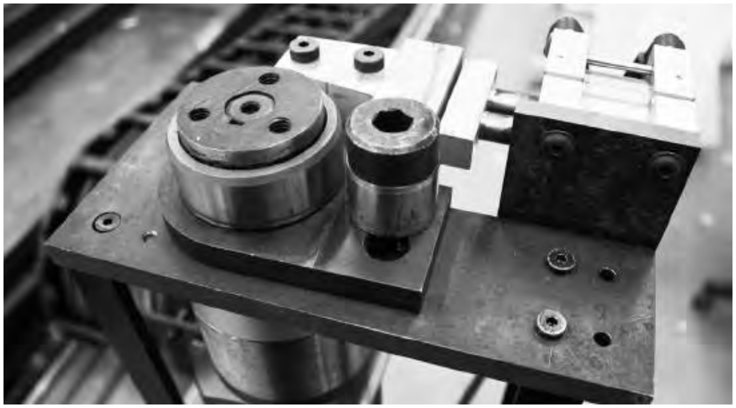

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8–10: Prototype tooling.

11: Bending process.

12: wavePavilion in-situ.

WAVE PAVILION
PARKE MACDOWELL & DIANA TOMOVA

wavePavilion is an architectural installation generated though computational processes and built using custom digital fabrication technology. Completed in June 2010, the project is located on the grounds of the University of Michigan's Taubman College of Architecture and Urban Planning, where it performs a didactic role within the dialogue of digital fabrication at the college. wavePavilion has a footprint of 20 x 30 ft and stands 15 ft tall, containing over 1 km of 1/4-in. diameter steel rod.

Incongruously, amidst the excitement of accelerating technological advances in architecture, this project began by looking backwards. Since the Renaissance, traditions of drawing have remained central to the discipline, contingent on a belief in the ability of the architectural 'line' to represent space. In recent decades, computer modelling has largely supplanted the power of line with that of 'surface'. While the ramifications of this shift are widespread, expressed in everything from the drafting table to the skyscraper, the dominance of surface is especially apparent in the still-nascent domain of digital fabrication. As the complex forms developed through surface modelling must be rationalised for production and assembly, mediating strategies like sectioning and panelling have emerged as prevailing idioms.

wavePavilion bucks this trend, discarding contemporary tropes and instead harnessing the potential of algorithmic computing to weaponise the line and instantiate it in the physical world. Hereby, traditional practices of drawings are reimagined as the impetus for a new tectonic mode, grounded in a simple monad of linear geometry.

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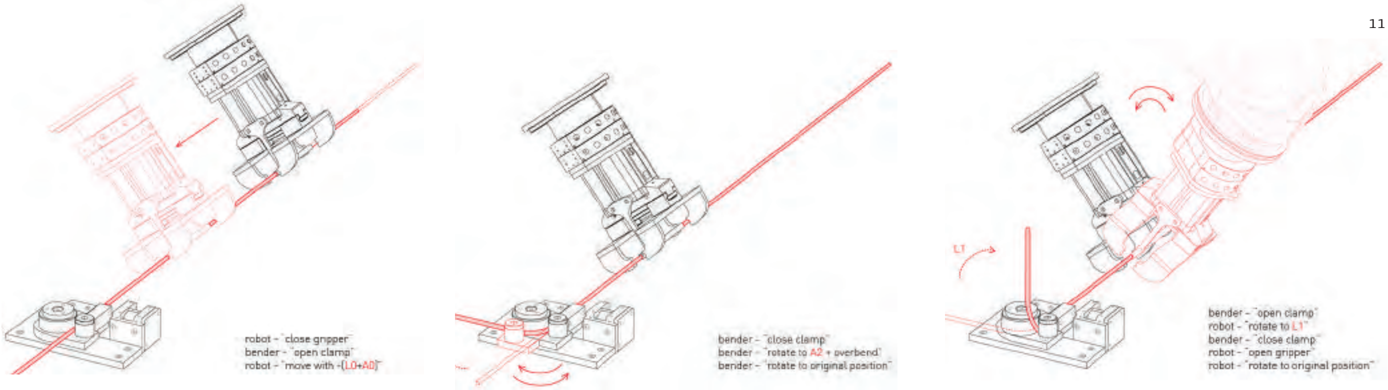
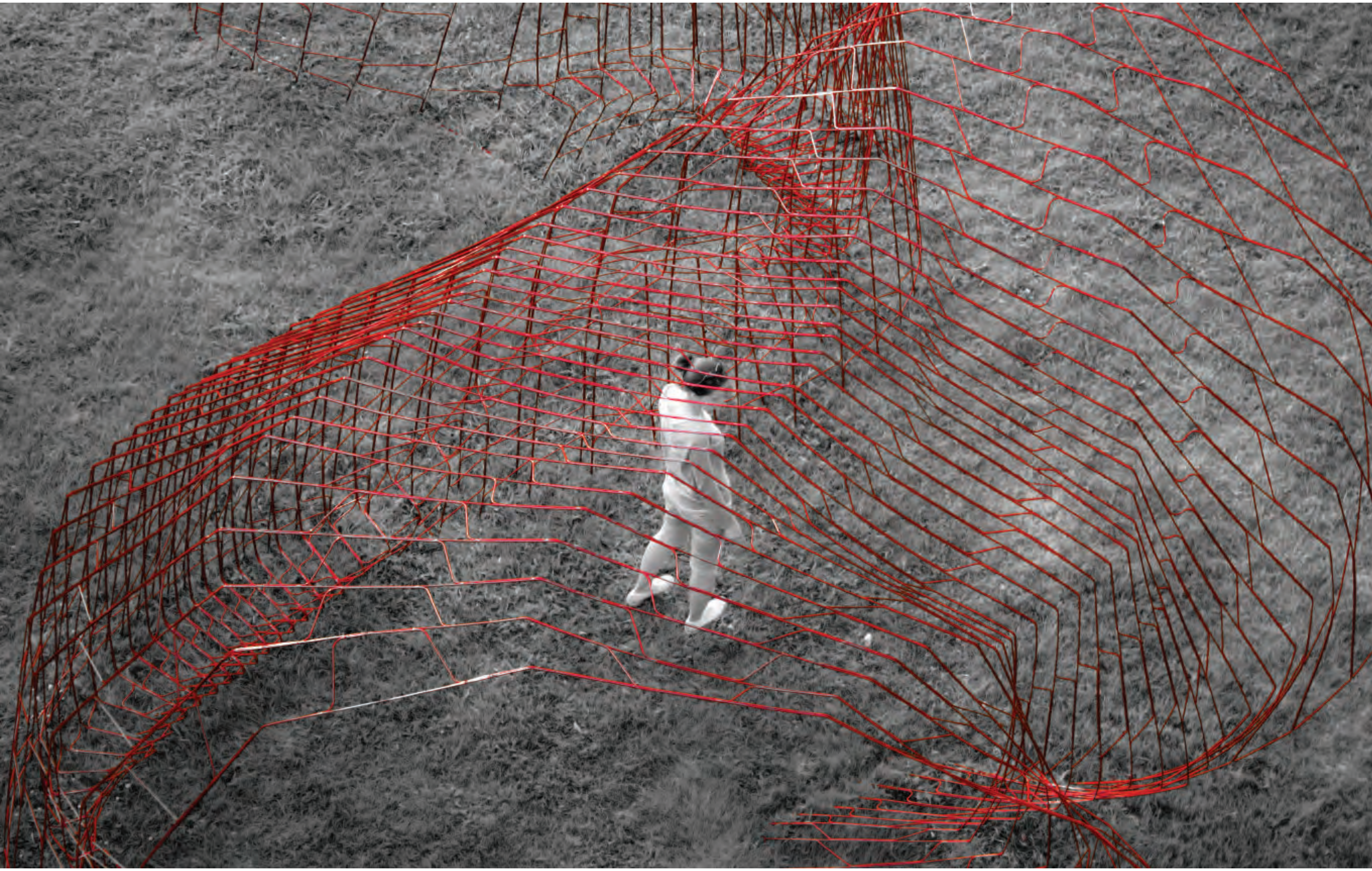

robot - "close gripper"
bender - "open clamp"
robot - "move with -(L0+A0)"
bender - "close clamp"
bender - "rotate to A2 + overbend"
bender - "rotate to original position"
L1
bender - "open clamp"
robot - "rotate to L1"
bender - "close clamp"
robot - "open gripper"
robot - "rotate to original position"

12



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13: As the Pavilion form constricts, the lengths of the components diminish, and structural pattern evolves into aesthetic gesture.

14: Strong sunlight multiplies the graphic qualities of the piece, reversing the translation from drawing to built form.

This crude but variable base unit, deployed within an assembly through complex relational logics, evokes qualities of surface and atmosphere. In so doing, the line becomes a means of challenging the ubiquity of the 'blob' within scripted/parametric form-making. Geometric composition, in this case, supplies all the complexity and nuance for which we have become enamoured of calculus-dependent surface modelling.

Digital fabrication has been heralded as a means of collapsing the long-standing divide that separates ideation and representation from construction. By extension, this argument asserts that the scope of architectural practice might be expanded and strengthened as the designer acquires greater control over the means of production. This stance cannot, however, be accepted without caveat. The enormous power of digital technology has the potential to run roughshod over the careless, subsuming the voice of the designer under the tendencies and biases of the 'tool'. Investing an ethic of design within the modes of production themselves is a way to put authorship back in the hands of the architect. As such, this work emphasises the development of tools and processes in tandem with the development of ideas and form, as a means of winning authorial power for the designer amidst increasingly mechanised methodologies.

COMPUTATIONAL DESIGN

The structure and aesthetic of wavePavilion developed through a scripted strategy of geometric evolution. This RhinoScript code combined programmatic influences with intrinsic formal tendencies to produce a unique, but situated, architectural object.

The virtual environment in which the pavilion form-script operates is established in Rhinoceros. This meta-site is seeded with critical nodes, which embed information tied to real-world spatial and programmatic requirements. This process generates a field of vector impulses, influencing the innate tendencies of the form-script. The script then tracks a course within the data-environment of the established vector field, demarcating a curve of primary structure that describes two zones, each with distinct views and orientation. The resultant spaces are simultaneously connected and autonomous, a perception reinforced by the modulating density of the developing pavilion form. A secondary array of geometry acknowledges the primary curve but follows its own. In the specific instance of wavePavilion, this new layer delaminates from the primary form at the end of its trajectory. This expression highlights the internal variation invested within a single form-making strategy.

A network of 3D polylines grows from the preparatory geometry on the ground plane. Each segment of these polylines develops with a specific scale and direction via a geometric negotiation between the innate tendencies of the form-script and the environmental parameters resulting from the critical nodes. As a kind of ancestor geometry for the final pavilion form, these polylines are the simple progenitors of a lineage from which more complex descendents evolve. The ancestor geometry establishes the broad morphological characteristics of the pavilion but lacks the sophistication to address issues of structural integrity and user occupation.

The descendent geometry takes the crude form of the ancestor geometry and augments it with a more nuanced understanding of proximity and spatial relationships.

New behaviours evolve, wherein individual components engage in physical exchange with their neighbours, forming aesthetic and structural alliances towards the development of a cohesive society of form. The late stage form-society displays broad networks of structural affiliation while also maintaining a high degree of local diversity. Behavioural gradients read across the breadth of the pavilion but moments of eccentricity – phase shifts, vestigial phenotypes, dormant features – reveal the complex relational processes of the underlying system. In such a way, the wavePavilion manifests an index of its own phylogeny, physically expressing its internal logics while also satisfying the pragmatic requirements of built, occupiable form.

ROBOTIC FABRICATION AND ASSEMBLY

The clarity of the project's conceptual impetus relied on the precise fabrication and assembly of its constituent elements. To this end, a multi-use seven-axis robotic arm was paired with a bespoke CNC rod-bending device. These specialised but versatile tools operated in tandem to shape multi-planar components out of 1/4-in. steel rod. A custom script was developed to analyse the digital geometry of the wavePavilion and translate that information into a series of operations for the bender and robot. This code breaks input geometry into lines and arcs and records data such as length and orientation for each element. The data is exported as a series of commands in KUKA code (for the robot) and hex-base machine code (for the bender). These commands choreograph the actions of the robot and bender in order to reconstruct the original digital geometry out of steel rod.

The bent components were organised with a simple indexing system, and transported to the site, where they were manually assembled and welded. The multi-planarity of each component is critical to this assembly process, eliminating the need for positioning jigs because each component can only align with its neighbours in a single, specific orientation. As part of this self-indexing assembly, each element fits precisely against the previous pieces while also guiding the positioning of the subsequent elements. Once positioned, the rods were manually welded in place.

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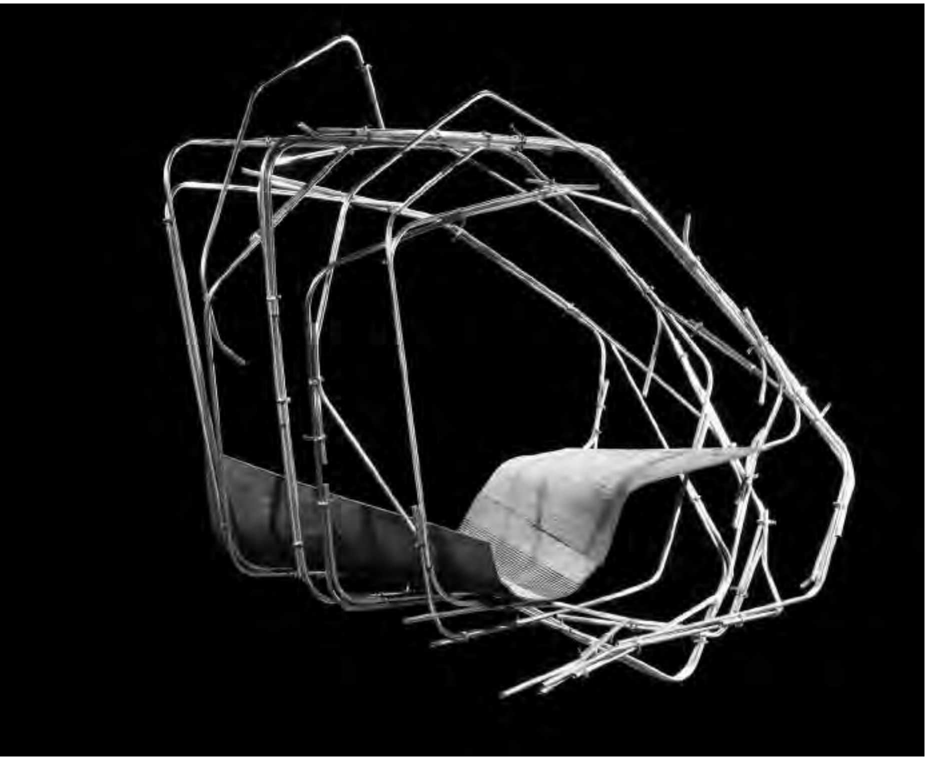
CONCLUSION AND PROJECTION

wavePavilion was a quick, two-month investigation that has initiated an ongoing trajectory of research. Both scripting and customised robotic fabrication embed a sometimes daunting learning curve that inhibits the potential of these tools and processes within an academic setting. With this in mind, the physical and computational tools developed for wavePavilion have been shared with designers, both at the University of Michigan and other institutions, in hope of accelerating the research through increased accessibility and open-source participation.

Small scale experiments by the authors and others have continued in 1/4-in. and 3/8-in. metal rod. Refinements to the toolset are also ongoing, and the next-generation bending device currently in development will expand this experimentation to larger diameter materials.

The viability of these processes, as evinced by wavePavilion, suggests the potential for more refined architectural applications: mechanical attachments might replace welded connections to increase assembly speed. Secondary membrane systems may be developed to provide enveloping capacities. The bent steel of the wavePavilion may even be paired with wire mesh and shotcrete to produce highly customisable structural forms.



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15: Constructed proof-of-concept model.

16: Although bending was performed by the robot, the elements were assembled by human hand.

Critically, wavePavilion opens the domain of digital fabrication to a host of non-conventional practices in which concept and instantiation are linked without the need for panelling, sectioning or other mediating strategies. The expansion of this preliminary exercise through knowledge-sharing between multiple designers will channel this potential toward new modes of spatial description and tectonic opportunity.

BENT KENDRA BYRNE & NICK REBECK

Looking at the seven-axis industrial robotic arm as the ultimate fabrication multi-tool, where seemingly any attachment can be invented, Bent opens up pathways for dialogue between design methodologies and fabrication processes. Low-level access to technologies developed for industrial automation, through scripting and software interfaces, leverages latent links between virtual protocols and tangible deliverables. It furthers 'digital craft' as a mode of practice, choreographing exchanges between physical material and digital processes while also positioning tooling as a generator for architectural design. Exploiting the production efficiencies of digital design and fabrication, a proof-of-concept prototype was produced using a feedback-loop algorithmic design process and custom fabrication workflow.

Bent started with the intent to develop the tooling and workflow to directly bend small-diameter steel tubing using the robotic arm. An investigation of bending technology precedents led to various conceptual designs – such as having the robot draw tubing around a stationary die or trying to replicate the functionality of a standard CNC bending machine – but in the end it was a robotically ergonomic version of a modest conduit bender that provided the solution. By essentially attaching a split conduit bender to a pneumatic gripper, the robotic arm was tooled to produce multiple bends in a single piece of steel tube.

Concurrent to the tooling development, the team conceptualised an architectural application for small-diameter tube bending: a lattice frame system made structural through bundling and branching. A series of algorithms were developed to layer pipe to form a room within a room. The tube as an isomorph for a virtual line was tested against fabrication processes and structural logics. Iterative feedback between the algorithms producing the structure and the performance of fabricated prototypes produced an evolutionary morphology of both the production and formal design.

Successive attempts at choreographing the interaction between the robotic arm and the tubing through sequential bends and rotations provided geometric parameters that were fed back into the lattice system's generative algorithm. Distance between bends increased and the relative angles between bends were limited. As the parameters were refined according to the fabrication constraints, a system of layered helices emerged from layering lines. Ultimately, the helical geometry of the prototype's lattice system was a product of material and tooling efficiencies afforded by algorithmic design and custom fabrication methods.

As the tool design and fabrication instructions were refined to reproduce bend angles in the digital model with a high resolution, material properties such as spring-back were written into the designed angles. The precision required to produce the desired bend angles called for the addition of a pneumatic clamp driven through the robot's external outputs to minimise unwanted rotation as the tool re-grips the tube. Through iterative study models, the team realised that the structural behaviour of the helical system asked for the tube to be slightly under-bent relative to the designed angle. The intentional under-bending brought each element into compression when assembled, giving the entire system greater rigidity.

The connection detail was chosen to play off the ductility of the material and its transformation into a rigid structure in the construction of the helical frame. The expandable and reversible hose clamp provides a standard means for bundling parallel segments of unique elements. The system provides its own jig for construction that is then built upon with layers of helical segments. As the layers are built up, the clamp expands to hold them in place. Once all of the layers are in place, the clamps are tightened and the helical frame is locked in compression.

In the standard conception of a structural frame, it is the connection detail that provides the means for linear elements to precisely join and orient at a point, creating a rigid lattice through iteration of the point-connection. Under this convention, each connection must be unique for the system to be variable. In this proposed rethinking of the frame as a helical structure, the fabrication method does the work of the unique connection detail through direct manipulation of the linear elements. The precision bend orients linear elements and the act of bending is iterated. The re-vision of the frame as being made of unique parts produced through a consistent process is tied directly to a design methodology that includes fabrication design as an integral part of the design process.

Since the structural logic of the helical frame is based on a process of additive layering, variation in the scale of the frame can be supported through additional layers of bundled pipe. As the scale increases, so does the number of points where the structure branches to brace itself. Although this project did not focus on designing a tool that can accommodate any diameter of pipe, increases in scale can also be supported by using larger diameter pipe. Since material properties are directly integrated into the script producing the formal design as well as the fabrication instructions, the same helical system can be applied at multiple scales. In a sense, the design is parametric in that changes in material properties, scale or overall form, are reflected in the output of the fabrication instructions.

The project ultimately produced a rubric for further work on relationships between design methodologies and fabrication processes. The prototypical helical frame should be considered an initial exploration of the first layer of a multiple component building system, and the rubric provides the framework for not only designing and fabricating additional component systems but also designing the interaction of the components as an overall system. In terms of composite systems, the ability to maintain a constant zero-point between fabrication processes allows materials to be tooled multiple times with a high degree of accuracy. The next phase of the work is looking toward interfacing other materials to develop a system to clad the structure.

For now, a fluid workflow between the virtual and the tactile was developed. A formal system of helical layering, bundling and branching emerged from material properties and custom tooling design. There is elegance in the legibility of the tool and fabrication process in the structural system, providing some transparency of the translation from the digital model to the physical form. The design of the tool is inseparable from the aesthetics of the formal system, inseparable from the architecture proposed by the prototype.

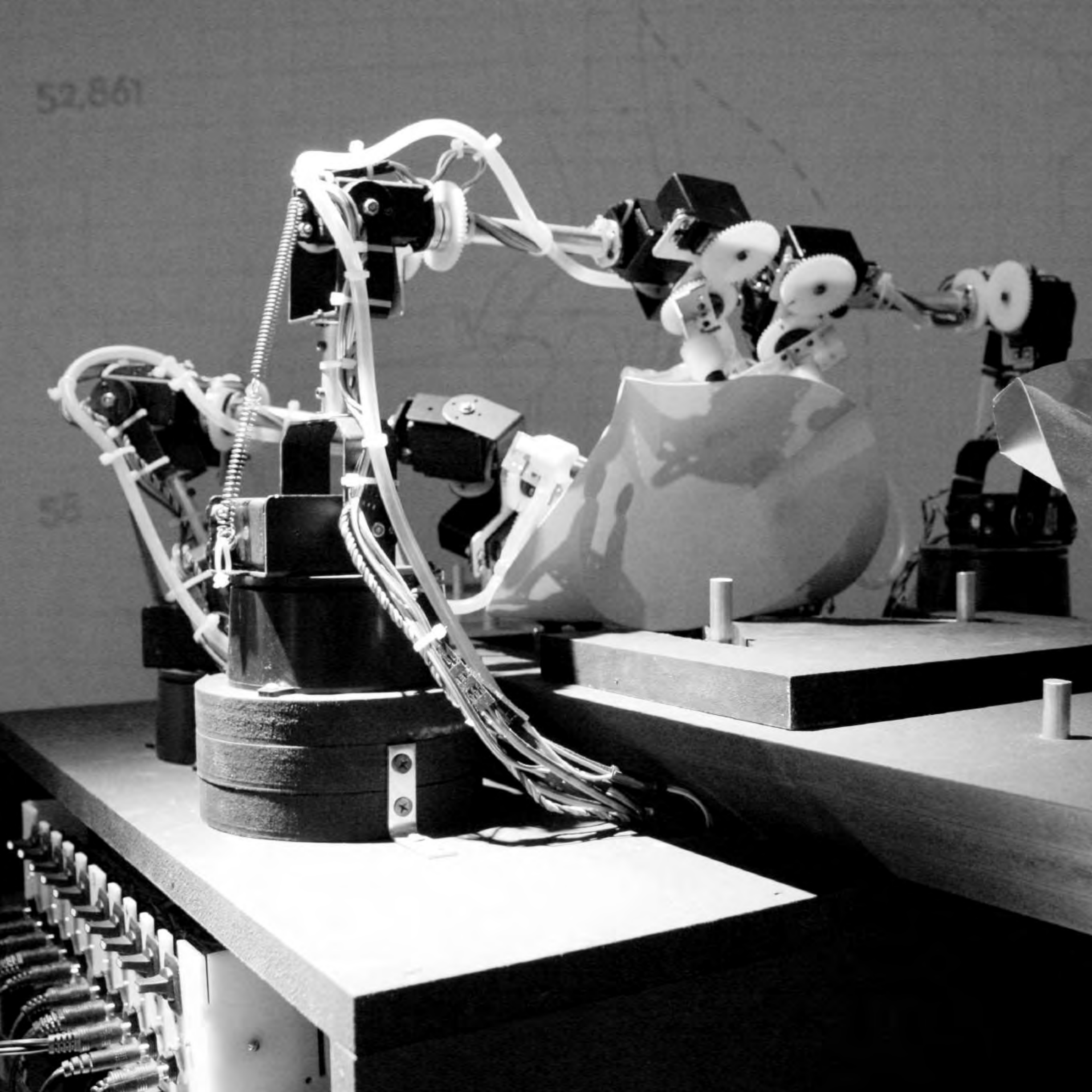
MATERIAL ANIMATION A NEW INTERFACE TO CUSTOM FABRICATION

NICK PUCKETT,
ALTN RESEARCH, THE UNIVERSITY OF KENTUCKY

Advances in architectural fabrication methods have historically stemmed from utilising existing, robust production systems in novel ways This is related to several factors, including the generally high cost of fabrication equipment, which can limit the scope of experimentation. Also, fabrication methods typically work on the basis that geometry is fed into a 'black box' algorithm, which generates the control code necessary to run the machine. This research presents a new method of control that interprets digital fabrication as a problem of animation rather than algorithm. The goal of this approach is to develop an interface and protocols that allow designers to develop experimental, highly custom fabrication systems intuitively and at a relatively low cost.

At its core, digital fabrication can be understood simply as a digitally controlled animation of physical systems. These physical animations have similar actuators at their core that can be predictably calibrated and mapped. Thus, by creating a new interface to this data, existing software and knowledge bases can be leveraged to expand the ability for new fabrication methods to emerge. The two case studies presented here utilise Maya as the controller for these custom production systems, due to its flexibility and strength as an animation tool. By operating within an animation and/or framework the control paths can be generated manually as a simple keyframe animation and/or through custom scripting tools. This human/computer hybrid system of input allows designers to implement direct fabrication decisions that may be difficult to programme while still leveraging computational tools as necessary. This also allows designers to draw on the large existing knowledge/code base with these programs typically used for digital geometry generation and create a closer link with fabrication.

The case studies here show the development of this work from utilising a flexible, standardised system of fabrication (a six-axis robot) to a completely custom fabrication system. In both studies the control data is created through a combination of standard and custom animation tools. The difficulty in this method lies in the calibration of the digital system to handle the 'physical realities' and relative accuracy of the physical counterparts in a manner that is both robust and predictable.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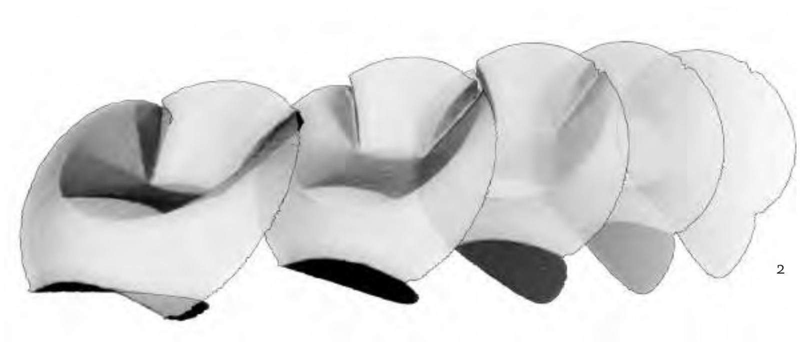
was to be made from a single sheet of folded metal. To do this, the form of the chair was developed in paper and then digitally scanned. A digital mesh of the finished chair was simulated to fold to a flat sheet by Evolute in Vienna. The folding process was inverted to create a singular mesh that animates from the flat to the final form. The simulation attaches robots to the digital surface at a specified point and, as the surface animates, it drives the kinematic chain of the robot. The distinct angle of each axis was then run through a calibration filter to determine the data sent to the servos.

At this stage the folding simulation did not take into account specific material properties or attachment points, so the surface served as a general guide to the physical forming. Deviations due to material properties were implemented via an offset layer in the software. In consultation with Gregory Epps of Robofold the placement of the grippers was determined by understanding the folding mesh as a quad mesh linkage that is broken into interrelated regions based on the major fold lines. Regions require a higher degree of accuracy, such as connection points, are given priority as they require more precise guiding, but as the linkage becomes more complex, fewer robots are required in relation to the number of folds. In this case, the four robots were used in pairs to create the two-crease details on the back of the chair that lock the form into place and the fixed arm is used to fold the bottom fin and hold the material so that the four-bots have the leverage to push the material.

At each simulated frame the angle of each axis per robot, the fixed arm and four solenoids had to be calculated, resulting in 29 values being sent to the hardware over a custom protocol. The solenoids where used to allow the pick-up and placement of the finished chair by controlling the suction of the vacuum grippers. To accommodate this, a custom circuit and controller were developed based on the Arduino platform. By embedding the digital model with the physical characteristics this process could be crafted digitally frame-by-frame as an iterative process between the physical and digital model. This direct control of the overall system made it possible to efficiently deal with the complex data required to operate the robots.



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ROBOFOLD

The initial research for this production method was done in collaboration with RoboFold to develop a proof of concept model for the company's production method. The proof-of-concept was undertaken at a scale of 1:5 using off-the-shelf, six-axis robotic arms that were retrofitted with custom vacuum grippers. The production model looks to eliminate the need for tooling by forming sheet metal with a system of curved-crease scoring and folding by the robots. The overall goal for the prototype was to create a system that allowed multiple robots to cooperate in order to fold an individual piece. An additional challenge is that robotic arms are generally used for pick-and-place operations rather than following a highly controlled path needed for folding operations. The goal was to create a digital model of the physical robots, that accounted for the variations in sizes and range of motion per axis, and a visual solver to determine the kinematic values necessary to fold a particular shape.

Robofold employed the system to prototype a fabrication process for Studio Joris Laarman's Asimov chair, which

FIELD CONDITION

Field Condition is a research project being undertaken at the University of Kentucky that examines the potential

1: Robotic production system developed with RoboFold for Studio Laarman.

2: Guide mesh. The mesh sequence generated by EVOLUTE takes a digital scan of a 3D model and simulates the folding of the mesh to a flat sheet.

3: Early Prototype of Field Condition mower. The cutting mechanism from a standard reel mower is retrofitted to two linear actuators controlled by an Arduino.

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of fabrication as a responsive system. The project looks to apply methods of digital prototyping to a highly renewable material: grass. The first iteration of this is the creation of a CNC mower cutting digitally generated patterns into variably sized fields. Whereas the previous work utilised a prebuilt mechanism this project is developing the fabrication mechanism from scratch. The goal is to create a mowing mechanism that can adjust its height and angle over a range of 0–150 mm to cut a specified pattern. The mechanism itself is constructed as a rolling frame that supports the cutting mechanism via two linear actuators. The actuators operate independently to allow both for height and angle adjustment over the course of each pattern.
The first iteration of the machine utilised a reel mower as the cutting mechanism as its overall footprint was relatively small and allowed for a higher resolution of cut. Initial tests revealed, however, that reel mowers are best for finer control and cannot handle taller grass limiting the overall depth for the relief cut. In its second iteration a string-trimmer head was used to allow for a greater depth of cut with a similar resolution.

The software system is designed to operate in either a real-time testing mode or a processed mode. In its former mode, the actuator values are fed in real time from the digital model, allowing for tuning of the system. In the later mode the digital cutting head is either animated directly or given a target surface to follow. Both of these methods result in an overall motion graph, which can then be fine-tuned. Once the path is determined the control code is output to the mower.

With Robofold, the complexity of the project arose from the amount of data that had to be passed to the robots per frame, but the overall output code informed each actuator at a fixed rate. In Field Condition the code generated is dynamic so that it can calculate the speed/heading and then adjust the rate that the values are fed to the actuators as a human operator pushes the mower over each strip. Each strip mowed can be understood as a single print line, but due to its mobile nature, the length of each line can scale almost infinitely. The challenge with this mobile method is to maintain control over the course of each strip, so an interface was developed to give speed and heading data to the operator. The software is written to be able to compensate for variations from the target speed within a set range and the interface provides feedback on relative speed to allow the operator to stay within it. This augmented production method further examines the relationship of a human/computer hybrid method of computation and control to allow direct input from the designer while also utilising a complex dataset.

MINIMAL COMPLEXITY

VLAD TENU,
THE BARTLETT, UCL

Minimal Complexity is the product of an architectural research project initially developed at The Bartlett, UCL, which focuses on both the form-finding and the fabrication of minimal surface structures. This process is defined by an alternative algorithmic method based on the computational simulation of virtual soap films. Therefore the project was focused on how the translation from the computational space to the build artefact could be embodied into this process. The algorithmic side of the project was developed in Processing 1.0.6., a Java-based programming language. The digital fabrication phase focused on testing and developing a series of systems for building generic architectural assemblies, based on the computationally generated geometries.

THE ALGORITHMIC PROCESS

Aiming to create a tool that could construct various types of triply-periodic minimal surfaces, the algorithm was based on the dynamic behaviour of a particle-spring system in order to simulate a tensioned membrane by using a bottom-up generative approach. The hypothesis was that a particle-spring net that defines a surface, due to the elastic properties of the springs, tends to behave like an elastic film, responding to forces and constraints. Accordingly, because of the tension, it achieves a minimal surface area between the defining boundaries. The solution for generating infinite triply-periodic minimal surfaces relied on establishing the system of constraints or forces that needed to be applied in order to satisfy the mean curvature characteristic and the topological configuration of the final surface.

The form-finding strategy was based on the properties of infinitely periodic minimal surfaces, generally composed of basic surface segments that are reflected in all three dimensions. The chosen case study was the Schwarz P-Surface, which addressed the problem of creating a basic surface region, enclosed in a kaleidoscopic cell, usually a tetrahedron. The tensioned membrane defined by the particles and the connecting springs, and bounded by the faces of the tetrahedron, illustrated a dynamic behaviour of a virtual soap film between the faces of the tetrahedron, hence a minimal surface. While the algorithm was performing a self-organising process of the particles, in order to define the geometry of the surface, the

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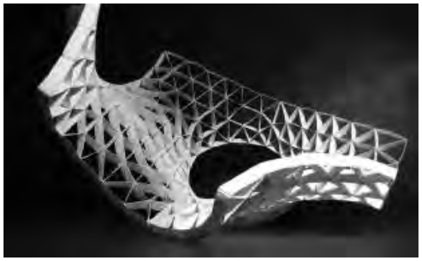

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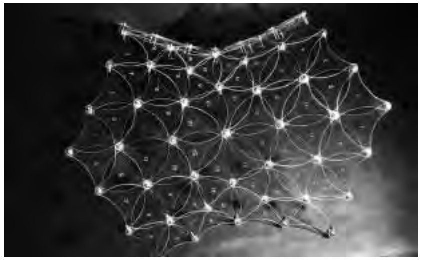

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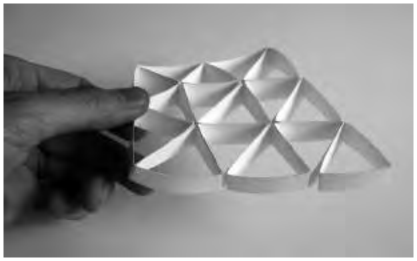

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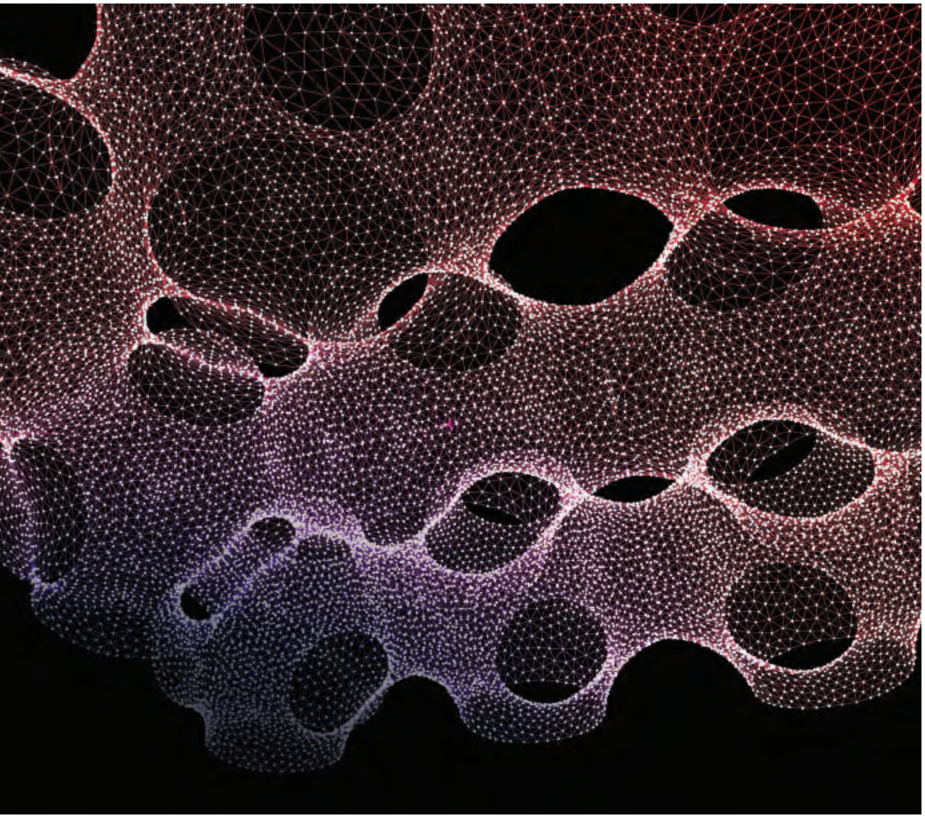

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1: Final work built by TEX-FAB in the atrium of the School of Architecture, Houston, Texas.

2–5: Physical tests on material and geometry.

6: Minimal surface geometries generated by the algorithm developed in Processing language.

7: Final prototype at 'Constructing Realities', Phase 2 Gallery, London.

springs were controlled by a customised Delaunay triangulation function to reach an efficient topology and uniform lengths tending to a pre-set dimension.

PROTOTYPING

The manufacturing side of the research focused on generating a geometry composed of standard-size modular elements. From the algorithmic point of view, the elements are the springs that connect the particles. As springs have the tendency to reach a defined standard length, they could form a homogenous system in which they would achieve a state of equilibrium as a geometry composed of similar-size linear elements.

From the fabrication point of view, the research focused on defining several systems for building architectural prototypes of minimal surfaces. The basic surface regions of the Schwarz P-Surface were developed based on a final geometry generated by 14 particles defining a very simple mesh composed of 16 triangular faces. All systems and prototypes were designed with the potential to apply them at a building scale as architectural elements. They consist in modular components build out of planar elements, cut and folded or mechanically fixed.

· The first system transformed the faceted geometry into a 3D structure by extruding every edge of the mesh, normal to the surface defined by the set of particles. The new planar elements would act as beams for the structure and give substantial rigidity for large-scale prototypes. The small-scale version was built from folded paper strips, forming 16 triangular components associated with the 16 triangles of the mesh.

· The interlocked rings prototype is based on having every particle (vertex of the mesh) as the centre of the circle defining the ring. Accordingly, each fundamental region would be composed of 14 rings. The result is a tensegrity structure with a high degree of flexibility.

· The Minimal Complexity prototype is the most developed system within the research, which created a set of components with a geometry built around the 16 triangular faces of the mesh. The shape of each component was derived from each facet within an instinctive design process, by taking into consideration the fixing mechanisms between them, the flexibility needed and the structural stiffness. The final piece is made of 1,936 laser-cut acrylic components, the equivalent of 121 basic surface segments each generated by 16 different shapes only. All the components were fixed with zinc-plated screws, nuts and washers. Various tests were initially made on different materials, such as mild and stainless steel plates. The assembly process was very interesting as it demonstrated how the fact that the minimal surfaces have extraordinary structural properties, uniform distribution of loads and how their stiffness increases in conjunction with their level of complexity. Accordingly, as the main parts of the piece were initially very sensitive to deformations, the final piece reached a greater level of rigidity.

· The Minimal Complexity structure was the winner of the TEX-FAB REPEAT Digital Fabrication Competition. Derived from the previous Perspex prototype, the 1:1 scale proposal is a metallic structure, more than 4.7 metres tall, built out of 2,368 laser-cut aluminum components, the equivalent of 148 identical sets of the same 16 components each. As a result of the change in scale, the use of finite element analysis (and hence use of different thicknesses of material for the components) and more efficient fasteners are all part of a more complex process of assembly.

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The main advantage and potential of these systems is that using only a very small number of different components (in our case 16), according to the level or resolution, we can aim for a specific structure, and can reach an incredible level of complexity of the generated shapes.

INNOVATIONS AND FUTURE INVESTIGATIONS

The research was developed around the design problem of minimal surface structures, and how to create an alternative algorithmic method for generating minimal surfaces as well as for building them from modular components. As opposed to the existing approaches in the field, this work utilises the principle of computational simulation of virtual soap films in order to generate minimal surface geometries, while also optimising them for a modular fabrication system. The main difference in approach comes from the bottom-up algorithmic strategy of not starting with a pre-defined topology, as in the case of the dynamic relaxation method, for example, but from simulating an iterative growth process, optimised to reach a state of tensional equilibrium of the system.

The modularity of the subdivisions of the resulting free-form surfaces could be extrapolated to various architectural applications such as facades, roofs, structural tensioned membranes or other types of architectural structures. The design framework is not limited to architecture, as the scale of the objects could reach the level of industrial design artefacts, furniture or installations. Due to the cellular logical structure of the system, in correlation with the interlocked circles that were used as a fabrication method, a feasible field of applications could include even fashion and textiles design.

The advantage of the proposed method lies in the ability to combine the two processes within a parametric system that could include more coefficients to be taken into consideration during the generative process. While a standard method would provide a 'rigid', strictly geometric or mathematical framework in defining a minimal surface without including the design factor, the generative proposed method could involve many new parameters besides the current geometrical and the modular ones, in order to solve spatial, morphological, social or structural design problems.

TERRA THERMA

PETER WEBB & MICK PINNER,
THE BARTLETT, UCL

The average depth of clay deposition beneath central London is 90 metres. It has been used as a building material since Roman times, and came into force as a mass material in the form of bricks, tiles and pipes after the Great Fire in 1666. The versatility of these units as durable and adaptable building components throughout centuries of use is hard to understate. So successful have they been that little about the way in which bricks, tiles and pipes are made has changed in this time. This project aims to rethink clay and the building components that are made from it. With the aid of digitally controlled tools, it investigates methods to extrude, manipulate and fire clay in the making of a building skin that is temperature- and humidity-controlled.

The catalyst for this research was based on a brief to design thermal baths in north London as a place for thermal recuperation. The site, located over the River Fleet, has for centuries served the city as a storm sewer. Thames Water are currently constructing a new sewer running under London for diverting overflow. It is set for completion in 2020 and will act as a catalyst for the cleaning of 'London's lost rivers'[1], including the River Fleet. Terra Therma is a speculative project intended for construction at this time, using the river to generate power and as a source of cooling, utilising the newly cleaned water for building purposes.

When fired, clay vitrifies, changing state from clay into ceramic/brick. The result is a material with a hard, porous structure that has a high resistance to weathering. It is initially bluish in colour and becomes brown when weathered. Characteristically, it has high compression strength, and because of this it has been used commercially for making bricks, tiles and pottery. The project was initiated with the development of custom digitally fabricated tools. This was achieved by laser-cutting die plates to extrude the clay through, with a framework to create the hollow. The die plates are attached to an auger extruder (pug mill). A number of different types of clay were tested including stoneware and earthenware clays. These experiments indicated the best surface finish was formed using red earthenware. London clay has great properties for extruding with and, when processed through a Pug mill past a die plate, it forms a smooth formed length of clay.

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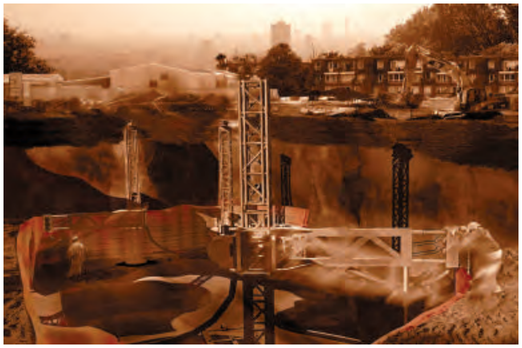

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1: Die plate and artefacts from extrusion tests.

2: 1:1 London clay building components through the baths.

3: Speculative on-site construction using London clay.

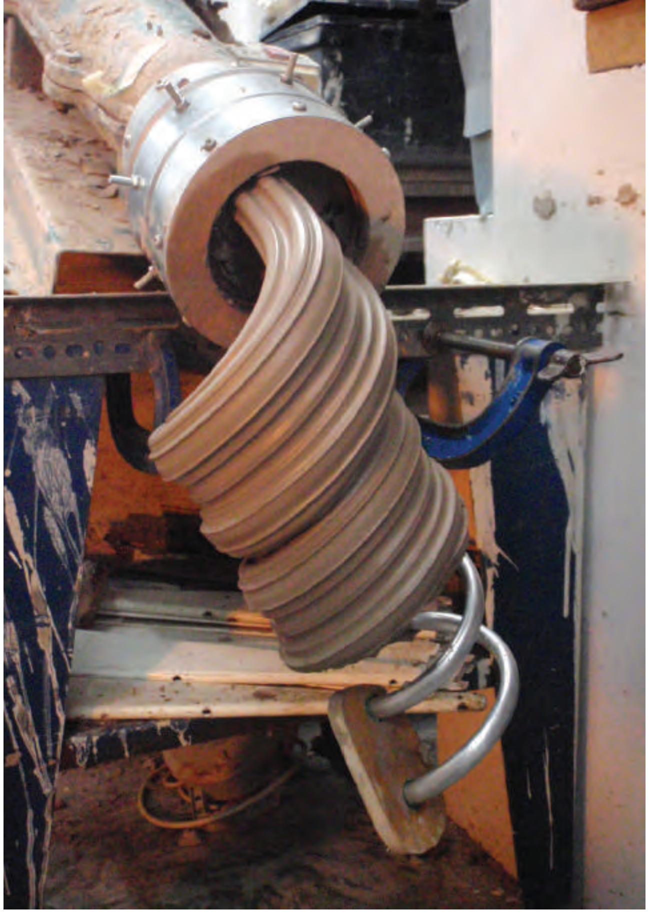
4–5: Custom rotational forming tools.

6: Internal perspective of thermal baths showing filtered river water flowing through the baths.

Early small-scale extrusion tests looked at ways of curving the formed clay after it had been extruded. A series of approaches were investigated, including using tracks of curved tubing, turntables, mandrels and excavations in the ground. Working directly with clay these forming methods influenced and opened up ideas about building components and how these could be stacked and joined or even hollowed out to create structural walls, facades and furniture. The surface pattern of the extrusion was designed using 3D modelling so that the extrusions interlocked horizontally and vertically. The secondary design principle was emitting heat: the curved profile gave the extrusion a larger surface area and fluid appearance.

To understand the quality of architectural spaces and potential compositions that could be achieved, the walls, integrated furniture, channels, water movements and thermal systems, were digitally modelled. The surface geometry was unrolled producing profiles calculating in the amount of shrinkage. These where then laser-cut and assembled to form moulds that were then extruded around before the clay was left to dry ahead of firing. Experiments suggested that the extrusions could be replicated on a larger scale from the same digital information.

Passing water through the extrusions with a pump, a thermal imaging camera was utilised to understand how the temperature of the clay could be manipulated. When exposed to sunlight there was a visual change in colour as water evaporated through the surface. Having



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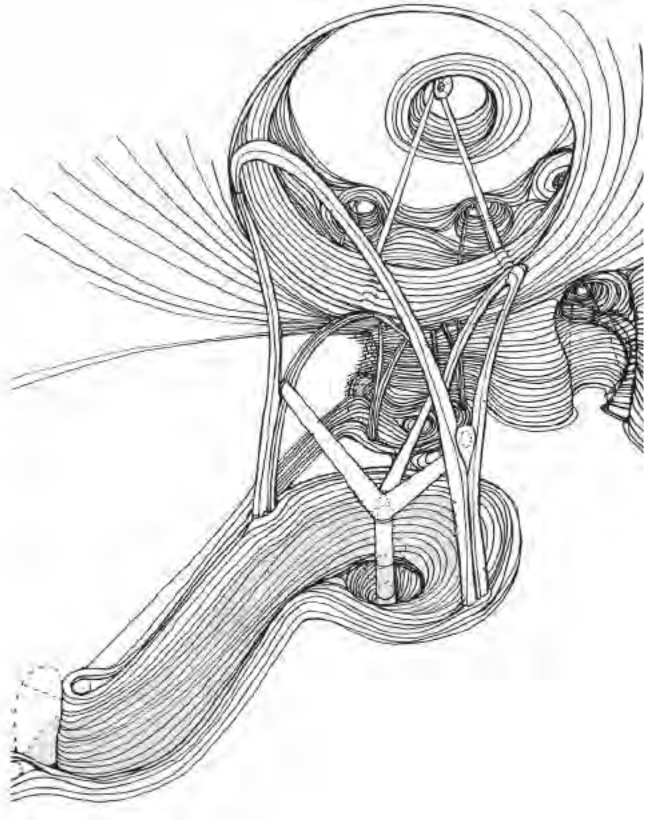

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created a series of physical prototypes, a collaboration was set up with West Meon Potters and Architectural Ceramists. Their facilities are capable of making 1:1 prototypes and they, too, were interested in combining digital fabrication with traditional techniques.

Moving to testing of 1:1 scale models, die plates were cut using a CNC router and installed into West Meon's pug mill. Methods for constructing a wall system with connection details so the extrusion could be joined together and allow water to pass through the hollow ceramic, were the primary objective. The surface and shape of the extrusion can be manipulated through a CNC-controlled plate changing surface pattern and wall thickness. With the extruder on tracks and a pivoting arm, complex wall-surface geometry can be constructed, providing a custom build on-site according to design.

These tests led to speculation about building construction systems, where the excavation of a site can be implemented using digitally controlled machinery with GPS technology, where 3D model geometry would enable for programming of the machine's movements and directly extrude the walls of the building according to the GPS parameters, building up the hollow walls on-site and constructing the building. Once extruded, the walls could then be fired with an electrical element – running inside the hollow ceramic – which would be digitally controlled to the right temperature, and covered in ceramic fibre to contain the heat. The ceramic fibre would then be taken away to reveal the hollow ceramic walls of the building.

Looking at the very serious environmental impact of the construction industry, the need to develop building methods with non-toxic materials is critically important. In the case of this research, the material may already be available on-site and experiments to date, combining digital fabrication technologies with clay, are promising. By comparison, metals, plastics and concrete have much higher levels of embodied energy, as they are rarely produced in the UK.

This project provides an alternative for building construction in the twenty-first century, specifically by looking at techniques of on-site construction – building from the ground, with simple tools augmented through digital processes. The forms and surfaces of the buildings constructed in this way can be tailored to site and use. The system integrates power and thermal control into a set of building components, as a way of fast, low-energy construction. This in turn would offer a fluid, long-lasting building from the ground up.

INVESTIGATIONS IN DESIGN & FABRICATION AT HYPERBODY

MARCO VERDE, MARKDAVID HOSALE & JELLE FERINGA,
HYPERBODY, TU DELFT

Under the direction of Prof. Ir. Kas Oosterhuis, Hyperbody is a research body at the Faculty of Architecture at the Delft University of Technology, the Netherlands. The primary research facility of Hyperbody is protoSPACE 3.0, a revolutionary real-time collaborative design environment. protoSPACE 3.0 is a unique, state-of-the-art multi-purpose laboratory for the development of non-standard, virtual and interactive architecture. In protoSPACE 3.0, Hyperbody explores these subjects through the development of 1:1 scale prototypes, file-to-factory production techniques and the development of immersive interactive environments. Although just a sampling of the research being conducted in protoSPACE 3.0 at Hyperbody, the following two articles provide a strong indicator of Hyperbody's approach to design and fabrication.

PROTODECK & PROTONODE · THE DESIGN OF AN INTERACTIVE FLOOR IN PROTOSPACE 3.0 MARCO VERDE ENG & MARKDAVID HOSALE

In its conception, protoDECK is a catalyst as much as it is an expression of architectural and interaction design.

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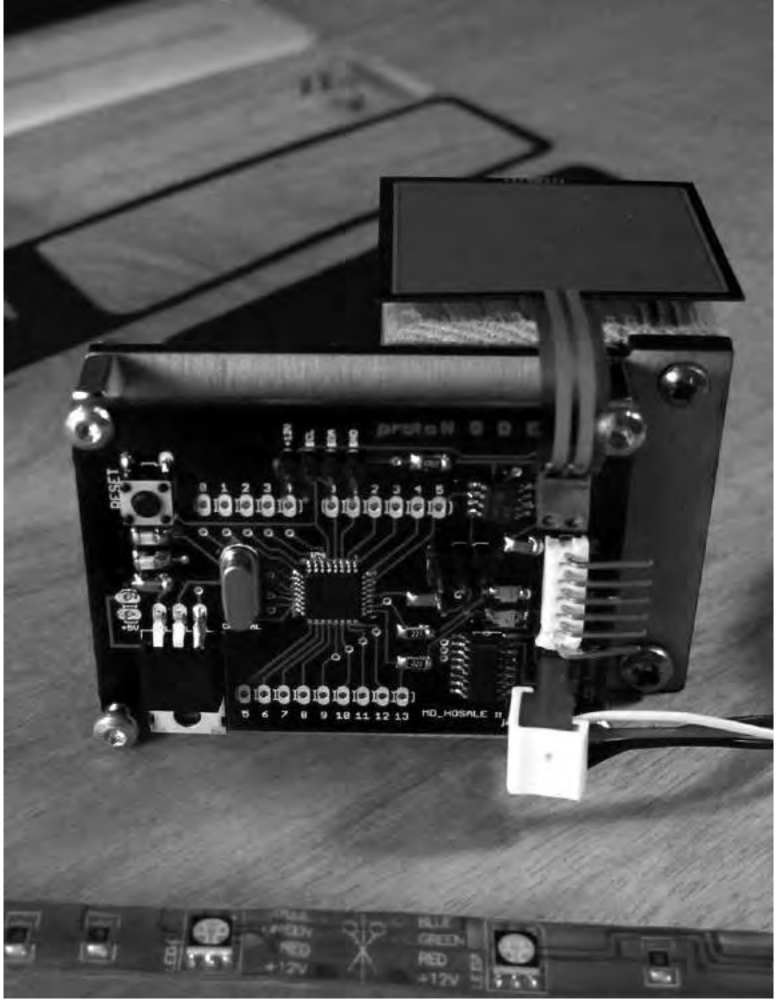

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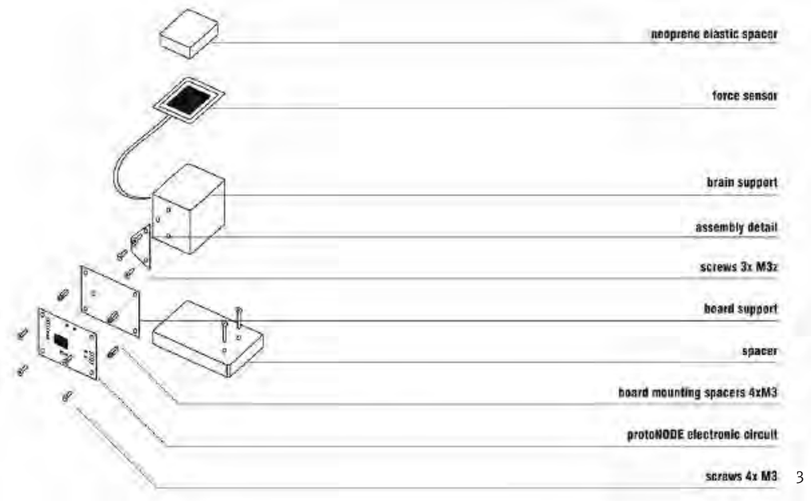

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Designed as an open system, it is both physically and behaviourally a modular system developed to embody multi-modal interaction, and to be adaptable to the research and education needs of protoSPACE 3.0. The design of protoDECK rises from computational design techniques and digital fabrication methods. It provides various current and future technical installations, upgrading the interactive experimentation lab at protoSPACE 3.0 through a modular system of interlocking, fully customisable wooden tiles.

The qualities of modularity and customisation have given rise to the behavioural system of the protoDECK. Out of a total of 361 tiles, a group of the 189 tiles in the centre of the floor have been organised into a behavioural group of responsive tiles. Within each of these tiles is a small, embedded microprocessor, called protoNODE. Each node is networked with its neighbours and is designed to give a tile a local intelligence, whereby it parses and interprets force sensor data from footsteps, and controls the output of a full-colour led lighting system. Each tile is therefore a member of a larger interactive system, which can be programmed with various behaviours to support numerous interaction scenarios. In addition to being fully programmable, the protoNODE is a physically modular system as well. Sensors and output devices can be added or removed to support future, unanticipated uses of the system.

MATERIAL PERFORMANCE INTO PARAMETRICS

The physical qualities of the component tiles of protoDECK are crucial to the performance of the system. The ability to collect, process and display information was implemented as an intrinsic feature of the design. The differential bending capacity of wood was understood as a physical/analogue input for the system, and it was strategically instrumentalised in its design and fabrication. The geometric make-up of the tiles became, therefore, especially important. Precise geometric and parametric relationships between the length, width, thickness and shape of the tiles had to be established to generate the final pattern of protoDECK. First, the entire area of the floor was described as a matrix of cells. Then, through parametric manipulation, a catalogue of alternative arrangements was developed and a configuration was selected. A system of 520 irregular cells defines the first

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1: Adapted hot-wire cutting machine.

2: protoNODE integrates a force-sensitive resistor and full-colour LED lighting system.

3: Overview of the protoDECK and protoNODE assembly logic.

4: protoDECK. A modular customisable interactive floor system.

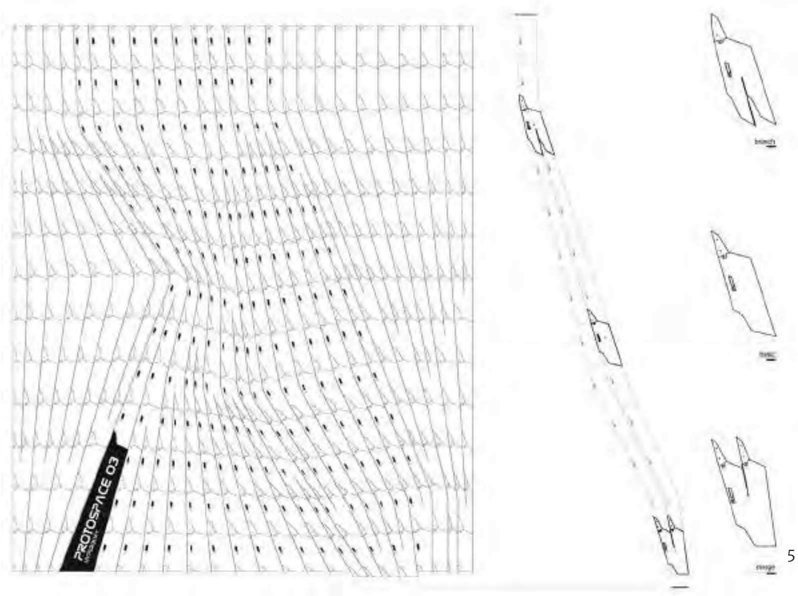
level of pattern organisation. Among the significant variables informing the selection criteria were the scale and total amount of components, the spatial organisation of the laboratory and the performative capabilities of the system.

PARAMETRICS AND PATTERN DEVELOPMENT

Upon the findings of the first stage, a second set of parametric processes was applied, aiming at a second level of pattern organisation. In this second stage a key feature of protoDECK is developed; that is, the shift in scale of its components. This programmed pattern formation process implies that, according to defined rules, individual cells of the matrix can branch and adjacent cells can merge along the pattern. The branching/merging logic is driven by physical criteria; it is meant to preserve the physical integrity of the component, its performance and its manufacturability. Given the protoSPACE 3.0 scenario, on the basis of a set of variables and constraints, a parametric system called ‘Matrix Scan System’ (MSS) was therefore developed to detect the cells of the system that should branch or merge to comply with the requirements. Finally, MSS becomes an instrument to search for multiple pattern organisations. From a wide catalogue of possible configurations generated through several iterations a final candidate was found. Selection criteria aimed at a strategic distribution of small- medium- and big-size tiles along the pattern.

DESIGN AND FABRICATION

As discussed, length, width, thickness and shape of the tiles are strictly entwined. It was important to limit the variation of the tiles to also comply with manufacturing and assembly constraints. Accordingly, the parametric system designed for protoDECK integrates manufacturing and assembly logic as parametric variables. The geometric features of the pattern are also related to the cost-effectiveness of the project. For example, given the protoSPACE 3.0 area, reducing the size of the tiles would imply increasing the amount of components needed to cover it (and vice versa). Having smaller tiles would imply that less material would be used per unit, but the number of components along the pattern would increase. Consequently, the total cutting length (i.e. manufacturing time) would increase as well, and fabricating the parts



5: Overview of the protoDECK pattern layout (left). According to the defined rule set, several scale transitions may occur along the pattern (right).

would become more expensive. However, having smaller elements would be an advantage because handling, assembly and transportation would also be easier. Finally, it was also decided that all parts had to be processed using only one cutting tool, to reduce the complexity of the manufacturing and engineering as well as the costs of programming. It is clear that an integral approach becomes important to catalyse all these factors into a unique system that is capable of preserving the qualities of the project from design to final materialisation. Finally, protoDECK and all its details are parametrically designed according to a CNC fabrication logic.

EMBEDDED ELECTRONICS AND BEHAVIOUR

protoNODE is a custom-designed embedded microcontroller based on the Arduino[1] platform. The development of a bespoke platform for protoDECK provided a low-cost solution (less than half the cost of standard Arduino), providing localised behavioural control to the 189 individual tiles of the centre of the floor system. Beyond the cost considerations, the development of a custom solution was an ideal approach for the integration of microcontrollers with the floor system, in terms of form factor as well as functionality. In terms of behaviour protoNODE is developed as an open media system designed to facilitate the needs of our researchers in the interactive experimentation zone of protoSPACE. The force-sensitive resistor and full-colour LED lighting embedded in each of the 189 tiles forms a collective whole, which can be conceptually understood as a large-scale, low-resolution, multi-touch screen. While the development of the protoNODE was based on a specific functionality, and the form factor was specifically designed to fit the floor, protoNODE is designed as an open platform. All of the pins on the microcontroller are made available so that new sensors, actuators, lighting systems, etc., can be readily added to a tile in order to facilitate unexpected and unforeseen future uses of the floor tiles. In addition, protoNODE can be easily adapted for use in future projects that connect to the floor or can even be independent systems of their own.

CONCLUSION

protoDECK is developed as a fully parametric-associative open system; hence, it is not a final object, but a field of possible futures. At component micro-scale, the local physical features of each constituent of protoDECK and their individual behaviour are programmed. At system macro-scale, the final organisation of the pattern and its features are only one example of the possible formalisations.
A combination of geometric interrelationships and algorithmic processes are responsible for local topological and morphological modulation; the interaction of these processes is responsible for the global behaviour of the system. The ability to collect and process information from the environment is implemented as an intrinsic feature of protoDECK design, rather than an additional functional layer. Moreover, the integration of 'file-to-factory' logic was significant to the development of protoDECK; hence, system configuration can be parametrically manipulated according to the spatial requirements of different project scenarios, and easily made ready for immediate CNC production.

An integral approach was needed for the success of project. Although it is a small project, protoDECK is a catalyst for a novel computational approach to architectural design. An interdisciplinary attitude fosters the merging of the architect, material engineer and manufacturer towards a holistic non-fragmented understanding of the process of design and making. Such an approach, fostered by the integration of contemporary computational processes, can finally contribute to the development of new spatial repertories and innovative strategies in design and making, while it also paves the way for the rethinking of architectural practice.

PROTOSPACE 4.0 MOCK-UP
JELLE FERINGA

Aiming to provide a new home to protoSPACE 4.0, a laboratory for collaborative design sessions, following the destruction of iWeb, (home to protoSPACE 2.0) by a faculty fire, Hyperbody has completed a large mock-up using an innovative hot-wire cutting method. Fabricating the expanded polystyrene (EPS) prototype in this manner offers interesting potential for the realisation of non-standard architecture.

WHY HOT-WIRE CUTTING?

Early in the development of the protoSPACE pavilion it was clear that manufacturing components by CNC milling was prohibitively expensive. CNC milling was found to be sub-optimal for the intended design for the following reasons:

- Placing the hexagonal components on the table of a large milling machine would require many transformations to make the object accessible to the milling bit. This re-positioning of the object being milled delimits the effectiveness of the milling process.

- Milling EPS foam generates considerable non-recyclable waste, which is costly to dispose of.

- Due to the fragility of the material it is necessary to protect the components when transported. Therefore, a partial negative shape of the component has to be milled as well.

Cutting the EPS blocks by heat rather than a milling bit results in a smoother surface and better finish. When cutting through with hot-wire, the process singes through the cells rather than splicing them open, making finishing the EPS foam with a coating easier. In the final design stages, the geometry was rationalised to developable surfaces, since a hot-wire machine by construction is bound to this category of form. Shaping the large foam blocks with a CNC hot-wire cutting machine offered an effective and efficient solution.

WHAT IS THE POTENTIAL OF HOT-WIRE FABRICATION?

Shaping volumes at an architectural scale in an accurate, cost-effective manner is a considerable challenge using any current digital fabrication methods. At Nedcam,[2] Hyperbody was able to evaluate machines that were sufficiently large for these applications. Their milling machines for example can remove a layer of 80 mm foam at a radius of roughly 15 mm at a speed of approximately 10 metres a minute, 0.012 cubic metres a minute, 0.72 cubic metres an hour. Rarely, however, will such rates be achieved, since these calculations assume maximal possible material removal, and no factoring in of the time it takes to position the milling bit. Other potential issues to note are that the surface is only roughened and unlikely to be an acceptable final product. In practice a material removal in the range between 0.2–0.3 cubic metres can be considered optimal. For CNC milling such rates are screamingly fast, certainly when taking the accuracy of the machined components into account. Large CNC milling installations are expected to only improve marginally in terms of the speed of material removal. Therefore, it is worthwhile considering alternatives that scale well to architectural proportions and, by all indications, hot-wire cutting is a viable alternative method.

An additional benefit of using hot-wire cutting is not just the effectiveness of the cutting process itself but also its coupling with expanded polystyrene. Building with EPS blocks is winning ground, but the approach has not filtered through to high-end architectural projects. EPS foam is both a very inexpensive material and perhaps surprisingly – a very eco-friendly material. It is not only friendly to the environment but also to the construction industry since it is lightweight. The advantage here is that building a large volume with EPS foam is easier and quicker for construction workers than traditional materials.

BUILDING THE MOCK-UP

During the construction of the protoSPACE mock-up, a number of observations regarding the intricacies of hot-wire cutting were made by Hyperbody. The following points identify a number of advantages in utilising CNC hot-wire methods:

- No waste. Material that was cut effectively provides packaging. The remaining pieces of foam can be recycled.

- The cost of a CNC hot-wire machine is a fraction of a milling machine of comparable scale.

- The hot-wire machine is relatively lightweight and simple to use, which means it could potentially be deployed on construction sites.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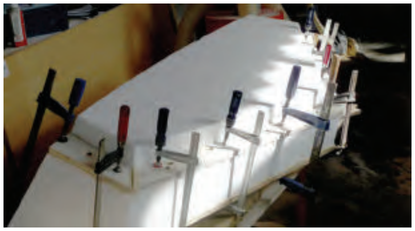
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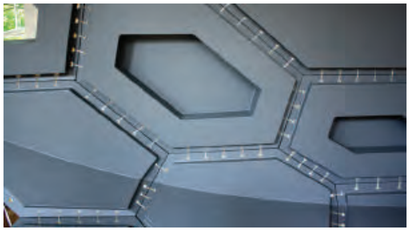
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· The components of the mock-up were produced in a cost-effective manner, representing about 20 per cent of the cost of producing the components by milling.

One significant problem encountered is that software tools currently available are primitive compared to milling software.

Komplot Mechanics' in-house built hot-wire machine was augmented with portals on the front and the back of the table along with the portals on either side. As a result, the reach of the machine was improved, consequentially leading to fewer rotations of the components needed to fit the projected toolpaths onto the machine. To produce 3D rather than 2.5D (extrusion type forms) it is necessary to project the contours of the shape on two planes that represent the portals of the hot-wire machine.

The temptation to script the projection of the toolpaths was avoided, since with each produced cell, Hyperbody gathered new ideas to improve the paths. There are a number of constraints that makes computing the projection of the toolpaths non-trivial. Rotation of the component on the machine has to be minimised. Both portals have to move at more or less the same speed: if a portal is standing still, the heat of the wire will burn a large hole in the foam block, or worse it could even enflame the material. Finally, toolpaths should cut top-down, such that the fumes from the melting foam can evaporate. If not, the wire is cooled down and the polystyrene will start to stick to it. When cut, a block of EPS foam 'sighs' and looses roughly a thousandth of volume. With a block of 2 metres, this 'sighing' effect accounts for a tolerance of 2 mm. The final finished components deviated about 5 mm.

CONNECTION DETAILING

EPS components were reinforced with wooden inlays where the edges of the individually cut components met. ID tags and holes were milled into the 18-mm-thick wooden inlays, providing the components with a connection detail. The components were finished by a 1-mm layer of poly-urea hot spray coating, which helps the distributions of stress in the structure over a larger area.

The wooden inlays spread the point loads of each connection more evenly over the coating, preventing it from tearing. Moment forces in the structure are transferred over the sides of each component, resulting in mere tensile forces in each connection. The EPS material comfortably withstood the compression forces. Effectively the EPS 'mould' became an intrinsic part of the structure. Connections between components were tested on their strength in different conditions (supported on two sides, overhang, horizontally, vertically and so on) performing well. No tearing or breaking occurred and the displacements due to bending stayed within tolerances. This can be largely attributed to the low weight of the components.

CONCLUSION

By working on the protoSPACE mock-up, Hyperbody have come to think of hot-wire cutting as a fabrication method with striking architectural potential. Apart from the hard geometrical requirements of developable surfaces there is a need for geometrical tools that can compute toolpaths that respect the aforementioned heuristics. There is a lot of ground still to cover, including in the detailing of expanded polystyrene. The Hyperbody Research Group continues to further develop these fabrication techniques, building upon the knowledge gained from the mock-up of the protoSPACE 4.0.

6–7: Komplot Mechanics's adapted hot-wire cutting machine. Extra portal built to allow cutting both longitudinally and laterally.

8–9: Connection detail of wooden inlays glued to the EPS block. Inlays are covered with a polyurea coating distributing stress over a larger area.

10: The mock-up assembled in protoSPACE 3.

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PROTOTYPE FOR A SPATIALISED INSTRUMENT

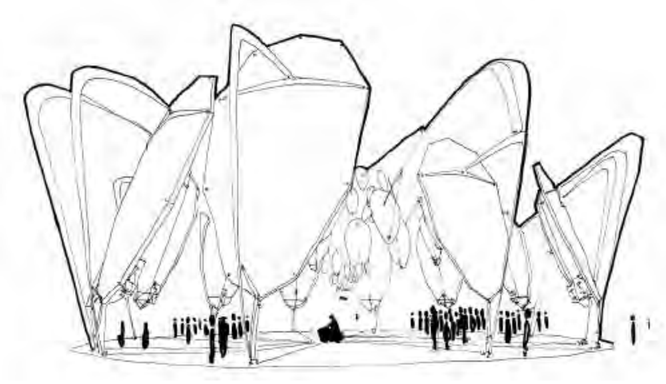
MISHA SMITH,
THE BARTLETT, UCL

A musical machine, an event, an installation and a sonic landscape, Prototype for a Spatialised Instrument explores and interrogates the relationships between instrument, player, composer, audience and location. Borrowing from the acoustic principles of piano construction, the bespoke musical instrument is arranged as an inhabitable environment intended to reveal new or different understandings of place, space and sound. A responsive environment, it is intended to challenge our appreciation of how sound interacts with objects, our bodies and our surroundings.

Architecture that deals with sound is predominantly space designed for sound – buildings for performance – however, this installation presents architecture as the performative provocateur. More than a passive container for sound, it actively shapes, modulates, conditions and makes sound. Developed in Diploma Unit 23 at The Bartlett, the project originated in Orford Ness on the Suffolk coast near Aldeburgh, where the composer Benjamin Britten lived and worked and established the Aldeburgh Festival for classical music.

The intention was to design a building that responded to this musical context, focusing in on the composer's instrument, a piano, a remarkable and surprisingly strange device on close inspection. It is a stringed instrument, but its tuning is pre-determined. It is a percussion instrument, and at the same time, a keyboard instrument – its strings are struck with hammers, but it is played with a keyboard. The piano is also compromised due to its size and the fact that its base strings are wound with copper wire to lower their frequency. Ideally the strings should be as thin and at as high a tension as possible. In light of these factors the project aimed to address the following question: what happens if you design a piano technically as it wants to be, and then design architecture around it?

The project deconstructs the piano, re-designing and fabricating it into a new spatial proposition. With 13 notes, each akin to a monochord constructed from the principle parts of a piano: frame, soundboard, strings and action. The instrument, however, does not have a keyboard, it is driven instead by an Arduino microcontroller and computer running



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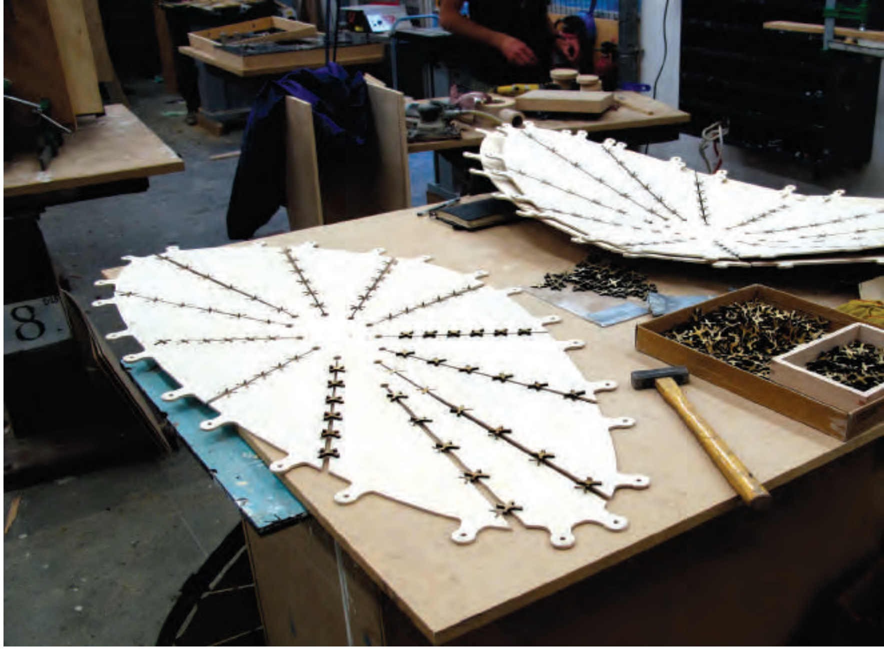

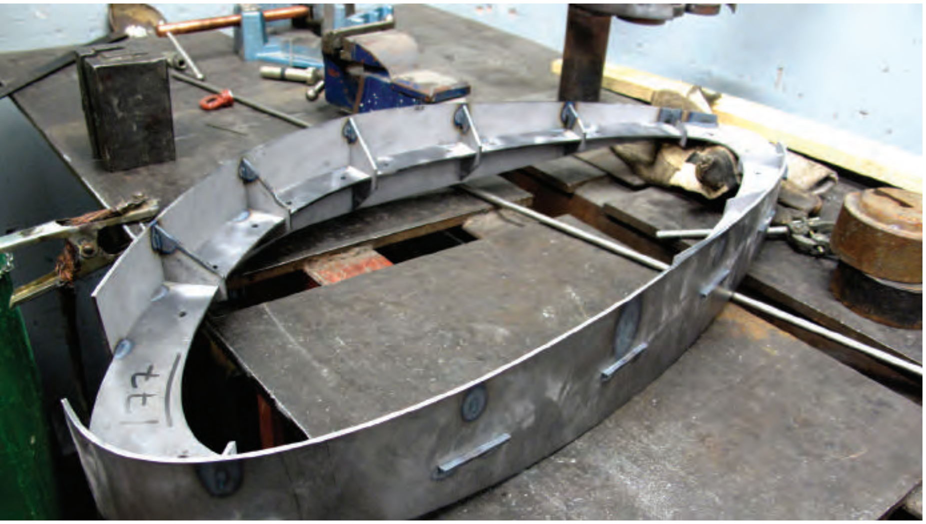

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1: Installation 4. Dispersed mode.

2: Idea sketch.

3:Digitally fabricated steel frame.

4: Soundboard forming.

custom software built in Processing. Solenoids placed on each note actuate in response to site conditions such as ambient sound and movement. The audience and elements of the site become players and composers of a generated, site- and time-specific composition. Exploring a range of potential relationships between location, instrument, player, composer and audience, a series of software programs were developed to drive the behaviour of the piece.

· Digital Player Piano: Pre-composed playback of arrangement using MIDI (Musical Instrument Digital Interface).

· Sound Recognition, Analysis and Interpretation: A Fourier transform algorithm, allowing ambient noise, someone speaking, singing or another musician playing, to interact with the piece.

· Body Presence: Infrared sensing to detect location of an audience.

· Motion Recognition: Using a live video feed, an optical flow algorithm senses motion, triggering a composition according to types of movement through and around a space.

· The project is a digital-analogue hybrid, both in terms of its design and the way it is made, and how it is played and interacted with – many of the parts are designed and cut using digital processes and then

4

assembled by hand; the sound produced is acoustic but generated by physical interaction with a digital interface. Through its development some of the possibilities that digital fabrication opens up to the architect are explored. Two types of manufacturing technology were used: laser-cutting, both steel for the frames and plywood for the soundboard stitches, and CNC routing for cutting the soundboards.

DESIGN AND FABRICATION

The frame of a piano is made from cast iron and has to withstand tension forces of around 20 tonnes. As each of the notes of the prototype were a different size, governed by the speaking length of string, 100 cm, middle C on a piano (261.626 Hz), to 500 mm, C one octave above (523.251 Hz), a method of making that would allow for bespoke one-offs was needed. The shape of the notes is partly generated by pragmatic considerations of structure: that the frame has to resist the tension of the strings while also supporting a soundboard of sufficient size that acts as a transducer and radiates their vibrations and is partly intuitive – developed through a series of models.

The notes were 3D modelled and the individual components extracted and flattened to produce digital cutting patterns. Achieving a perfect fit between parts and accurately jigging and aligning pieces in order to weld them was difficult and time-consuming to do by hand. This led to the development of a self-jigging frame kit with interlocking slots and tabs that required no more than a single clamp to align the pieces. The ring piece acts as the former around which the edge pieces are bent whilst a series of stiffeners hold the edge and ring at 90 degrees to one another. The soundboard requires a belly to vibrate freely. The soundboard was modelled, cut and flattened virtually and stitch profiles added in 2D. The patterns cut out on a CNC router were finished by hand. The 'stitches', also ply, were laser-cut due to their size and tested in 0.05-mm-size increments to achieve a tight-friction fit. Half of the first set of soundboards broke whilst they were being formed into shape.

Experiments with steaming ply, the sequence of stitching the seams, types of ply, seam spacing and pattern were explored in order to avoid the board cracking. A technique was developed to bring the whole board up into shape in one go using zip ties, to avoid over-stressing any one area of the board. The pin block, hitch pins and capo d'astro bar were all made by hand, and the actions from an old piano were fitted to a new bracket that set the relative positions of the hammer and damper. The bridge connecting the strings to the soundboard is a critical component and was templated once the soundboard and strings were in place, drawn on computer and then laser-cut from mahogany to ensure even foot contact and pressure.

CONCLUSION

Prototype for a Spatialised Instrument, made possible and affordable by digital fabrication tools, is crafted through a reflexive process of making and digital modelling. As the design spaces of the architect and the fabrication spaces of the manufacturer close, it suggests a more refined understandings of detail and material can be found through such processes. The role of the drawing changed as each line represents not only the finished article but the process of making it – the act of drawing and the act of making become inseparable.

This project has become the starting point for a longer-term proposition for the exploration and investigation of sound and architecture. Future collaboration with performers, dancers and musicians will test the boundaries and possibilities of the prototype. The exploration of scale – building the notes at the extremes: the bottom A and the top C – will present particular problems associated with manufacturing, transport, hammer and action operation, volume, decay and sustainability. Experimentation with further soundboard materials and manufacturing techniques, testing CNC-milled spruce, moulded carbon fibre and formed aluminium, are all ways in which the volume and tone quality of the instrument could be improved or varied. Further opportunities include installing dynamically adjustable tuning, so that it tunes and re-tunes to site feedback, and the addition of a 'bowing' mechanism as a means of playing to produce a constant spatial drone. Currently under development is a spatialised instrument, the form and size of which is dictated by its installation, site and an enclosure for the current prototype, whose size and form is derived from the resonant frequency of the 12-tone equal temperament tuning.

Q&A

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MATTHIAS KOHLER

Matthias Kohler is joint partner at the architects' office Gramazio & Kohler, Zurich. Recent works include the sWISH* Pavilion at Expo.02 (for IBM and Swiss Re), the new Christmas illuminations in the Zurich Bahnhofstrasse and the contemporary dance institution 'Tanzhaus Zurich'. Part of his professional activities include developing innovative construction and material solutions. Owing to his interdisciplinary experience, Matthias Kohler has a well-founded and specific understanding of the integration of CAD/CAM logic into the architectonic and construction process.

Kohler is also professor for Architecture and Digital Fabrication at the Department of Architecture, ETH Zurich. His research activities concentrate on the development of fabrication processes for the additive production of highly informed, non-standardised architectonic products. Parallel to this, he develops strategies for architectural design that are capable of working with these new production possibilities. These are explored within the teaching process in terms of their architectonic, constructive and economic potential. Prior to this he developed an industrial robot installation with a processing space of approximately 6 x 3 metres that can be used for research and teaching and which permits the direct construction of building parts on an architectonic scale.

HANIF KARA

Hanif Kara is a Co-founder and Design Director of London-based structural engineers, Adams Kara Taylor. The 'design-led' approach of AKT has allowed them to work with leading architects and designers on unique, pioneering and innovative projects.

His approach extends beyond the structural engineering disciplines and has led to his appointment as a commissioner for CABE (Commission for Architecture and the Built Environment). Kara was selected for the Master Jury for the 2004 cycle of the Aga Khan Awards for Architecture and was made an Honorary Fellow of the Royal Institute of British Architects in the same year. His work is also linked with the research and education areas of design and he co-tutored a Diploma Unit at the Architectural Association in London from 2000–2004. In 2008 he accepted the position of the visiting Pierce Anderson Lecturer in Creative Engineering at the Graduate School of Design, Harvard, and is visiting Professor of Architectural Technology at Kungliga Tekniska Högskolan (KTH), Stockholm, Sweden.

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MARK BURRY

Professor Mark Burry has published internationally on two main themes: the life and work of the architect, Antoni Gaudí, and the integration of theory into practice with regard to 'challenging' architecture. He has also published widely on broader issues of design, construction and the use of computers in design theory and practice. Burry has been Consultant Architect to the Temple Sagrada Família since 1979 and, in 2004, was awarded the prestigious 'Diplome i la insignia al'acadèmiccorresponent' by the Reial Acadèmica Catalana de Belles Artes de Sant Jordi in recognition of his contribution to the project. In 2006 he was awarded an Australian Research Council Federation Fellowship and was recently the recipient of the Association for Computer Aided Design in Architecture Award for Innovative Research.

Burry is director of RMIT's state-of-the-art Spatial Information Architecture Laboratory, which has been established as a holistic transdisciplinary research environment dedicated to almost all aspects of contemporary spatial design activity. The laboratory has a design-practice emphasis and acts as a creative think tank accessible to both local and international practices, including ARUP, Melbourne and London, dECOi, Paris, and Gehry Partners, Los Angeles. Burry is also the Founding Director of RMIT's new research initiative, the Design Institute.

MARK WEST

Mark West is the Founding Director of the Centre for Architectural Structures and Technology (CAST) at the University of Manitoba's Faculty of Architecture. CAST is a unique laboratory/studio/atelier, focused on the invention of new construction methods and new architectural forms by combining the disciplines of architecture, engineering, sculpture and drawing. West is the inventor of numerous fabric-formed concrete techniques for architectural, sculptural and structural applications. He is an Associate Professor of Architecture at the University of Manitoba, with cross appointments in the Faculty of Engineering in Manitoba, and the Department of Architecture and Civil Engineering at Bath University in the UK. As an artist, his work includes both public sculptures and a large collection of exploratory drawings. He has worked as an architectural educator for nearly 30 years in Canada and the US. He first trained as a builder, and then obtained a BArch. from the Cooper Union in New York, and a post-professional MArch. from Carleton University in Ottawa, Canada. His work has received wide recognition through publications, awards, lectures and exhibitions in the US, Asia and Europe.

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PHILIP BEESLEY

Philip Beesley is Associate Professor at the School of Architecture, University of Waterloo. His projects feature interactive kinetic systems that use dense arrays of microprocessors, sensors and actuator systems arranged within lightweight 'textile' structures. These environments pursue distributed emotional consciousness within synthetic and near-living systems.

His Hylozoic Ground project is a uniquely Canadian experimental architecture that explores qualities of contemporary wilderness. Exhibited at the 2010 Venice Biennale it was comprised by tens of thousands of digitally fabricated components fitted with meshed microprocessors and sensors. This glass-like and fragile artificial forest was constructed from an intricate lattice of small transparent acrylic meshwork links, covered with a network of interactive mechanical fronds, filters and whiskers. Similar to a coral reef, it followed cycles of opening, clamping, filtering and digesting.

Beesley's work is widely published and exhibited. He has received awards from VIDA 11.0, FEIDAD and has been the recipient of the Prix de Rome in Architecture, Canada.

MICHAEL STACEY

Michael Stacey is Chair in Architecture and Director of the Architecture and Tectonics Research Group at the University of Nottingham, where he leads the Zero Carbon Architecture Research Studio. He is also Research Professor at the University of Waterloo, Ontario. His research is centred on extending the boundaries of the possible, whilst combining quality and affordability, thus informing the built environment and the well-being of humankind.

In 1987 Stacey co-founded Brookes Stacey Randall Architects and, in 2004, he re-established Michael Stacey Architects. Key projects include: East Croydon Station, Thames Water Tower, Wembley Gateway Urban Regeneration Masterplan, Enschede Integrated Transport Interchange, Art House Chelsea, Expertex Textile Centrum and Ballingdon Bridge.

Stacey is the author of a wide range of publications including the following books: *Component Design* (2001), *Digital Fabricators* (2004), *Concrete: A Studio Design Guide* (2010) and *Making Architecture with Dr Darren Deane* (2011).

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NERI OXMAN

Architect and designer Neri Oxman is Assistant Professor of Media Arts and Sciences at the MIT Media Lab, where she directs the Mediated Matter Research Group. The Group explores how digital design and fabrication technologies mediate between matter and environment to radically transform the design and construction of objects, buildings and systems. Oxman's goal is to enhance the relationship between the built and the natural environment by employing design principles inspired by nature and implementing them in the invention of digital design technologies. Areas of application include product and architectural design, as well as digital fabrication and construction.

In 2009 Oxman was named by *ICON* magazine as one of the 20 most influential young architects and was also selected by *Fast Company* as one of the '100 Most Creative People in Business'. Her work has been exhibited at MoMA and is also part of the museum's permanent collection. Other exhibitions include the Museum of Science, Boston, the FRAC Collection, Orleans, France, and the 2010 Beijing Biennale. Oxman has received numerous awards, including a Graham Foundation Carter Manny Award, an International Earth Award for Future-Crucial Design and a Metropolis Next Generation Award.

SEAN HANNA

Sean Hanna is a Lecturer in Space and Adaptive Architectures at UCL, and director of The Bartlett Graduate School's MSc/MRes programmes in Adaptive Architecture and Computation. He is a member of the Space Group, noted in the 2008 Research Assessment Exercise as the highest performing research group of The Bartlett, which itself has the highest proportion of 4*, 'world leading', research in the field of Architecture and the Built Environment in the UK. His current research is primarily in developing computational methods for dealing with complexity in the built environment, including the comparative modelling of space and its perception by machine, and he is on the advisory boards of two UCL spin-out companies developing related technologies. Prior to academia, his background is in architecture and design practice, in which his application of design algorithms includes major projects with architects Foster + Partners and sculptor, Antony Gormley. He has published over 30 research papers, addressing the fields of spatial modelling, machine intelligence, collaborative creativity, among others, and is on the editorial boards of two specialised engineering and design journals relevant to the field. His work has been featured in the national and international press, including recent articles in *Architects' Journal* and *The Economist.*

MATTHIAS KOHLER
HANIF KARA

Hanif Kara / How is digital fabrication really altering design practice?

Matthias Kohler / Digital fabrication offers architects a first-hand experience of gaining an explicit control over the fabrication and manufacturing of architecture. Up to now architects have considered constructive issues mainly on a conceptual level. They were integrating their constructive knowledge in a rather implicit way into their designs. This becomes different with digital fabrication. Drawing a line or writing some code becomes a direct instruction to 'make'. This explicit connection between design and making leads to the renegotiation of the different roles of the participants, both in the design and planning process of architecture, as well as the building and construction process.

HK / Do you think that architects have sufficient knowledge of 'explicit qualities'? I ask, because even my knowledge in certain materials as a structural engineer is being superseded so fast I sometimes don't have the confidence to say that I have certain explicit knowledge. Do you have that difficulty at all?

MK / Yes of course.

HK / How do you deal with it?

MK / I don't believe that the architect should be overruling the experts, the contractors or the craftsmen working with the material on a day-to-day basis. I believe in new modes of collaboration. I am convinced that, in the near future, more and more information will be provided very explicitly by architects. This information is transmitted to machines that actually build from this data. So in some instances there is no other person re-evaluating or transforming this information anymore. What is interesting to me, is how architects unleash potentials created by this new situation.

HK / I was asking because I think your work is one of the few I would stand up and fight for on this issue. I was asking the question as perhaps the so-called experts in fabrication and construction are not always as good as we are led to believe, so I'm hoping that you might be saying that you and I, in our own discipline, are holding the pencil again, rather than relying on all these other disciplines that are costing and managing our processes. I was hoping you would say digital fabrication changes all of that because of our ability to control the work Am I putting words in your mouth?

MK / Slightly but that's OK. I think architects need to proactively develop their own design culture; meaning that they develop their own technologies as part of their professional culture and expertise. Therefore, and that's what I meant by 'renegotiation', the architects today can make themselves become the leading experts in the field of digital design and fabrication instead of passively waiting for technologies to develop around them. They have the opportunity to stand up for their knowledge and regain their terrain in terms of interdisciplinary expertise.

HK / That's clear and refreshing. So, if that's the direction you are going in, what are the main developments required to push this technology further?

MK / We have a challenge to build up a contemporary design culture. If you look at how, for example, once-novel materials such as concrete, glass or steel affected the expression of architecture at their time, you realise quickly to what level technological developments have always been intrinsically linked to architectural design. If architects just wait on what other disciplines develop they become selectors in a catalogue of possibilities, but they're not drivers of their own culture and they lose their specific experience and knowledge. So I would argue that what is needed today is a design and research culture integrating the material basis of architecture with a new computational reality through digital fabrication, and this can only be done by architects themselves.

HK / I can relate to the need for new design and research culture but how do we achieve it? My own opinion is that multidiscipline organisations don't work. I strongly believe in single disciplines, but an interdisciplinary conversation. Trying to loop practice and education, even before we talk about bridging the gap between practice and construction, is difficult. There are very few exceptions, yours being one, where I see this combination manifesting itself, and producing real things. Without this they become highly academic to practitioners. How can we make this mainstream, or do we need to be concerned about making it mainstream?

MK / First of all I think there is a need to dare and be self-confident. We only need an understanding of what is conceptually important to architecture, we don't need to take over the complete knowledge of other disciplines. We need to be selective about what is relevant to architectural discourse. Secondly, it is wise to start in education.

It's where a lot of our energy has been going in the past years. What we try there, in a very pragmatic way, is to empower students to learn from physical constructive experiments and transpose that into computer programming. This brings them into the control of a robot that builds what they conceived. Even though those projects remain at an experimental scale, we provide students with the fundamental experience that they can be in explicit control over a material fabrication process, and that they can integrate such constructive processes in their design concept.

HK / And have you had any feedback from graduates, I'm just wondering whether they have experienced any dichotomy or antagonism towards the digital in practice versus analogue or industry?

MK / I can tell from discussions with students that they appreciate the span of the experiences they encounter in our course. It's probably a bit too early to come to conclusions. Our goal is that the experience of being in control of digitally driven processes results in a proactive attitude. We hope to see the effects in 10–20 years, once these graduates establish their own practices.

HK / What are your thoughts on the issue of IPR (Intellectual Property Rights); because this is a new and interesting territory, and are people trying to over-protect the required knowledge?

MK / To be honest we haven't been thinking about IPR too much because our main focus has been on advancing the design research. I am not too worried if other projects seem familiar to some of the works we have been doing. To some degree, in architecture, it seems normal and necessary; that original work is being referenced and improved, even at the risk that it is sometimes just copied badly. What I don't like is when concepts get lost by those that take it up; and key discussions about the projects and their development is not being taken on.

HK / My concern is that the combination of a lack of creativity and richness in architecture, with the attempt to over-protect it, is killing some of the potential in digital fabrication. Your work, when I first came across it, was a rare moment where the opposite was promoted; by showing people your work whenever I can, I say these people were doing this five or six years ago, why can't we all be more creative and imaginative about this and stop over-protecting stuff.

MK / I agree, thoughts need to be shared in order to become culturally relevant. It is not fruitful to the evolution of the field to overprotect ideas as an academic or practitioner. In our own research we are less involved in commercialising ideas than in bringing developments to a point where they can be taken further by colleagues or eventually by industries.

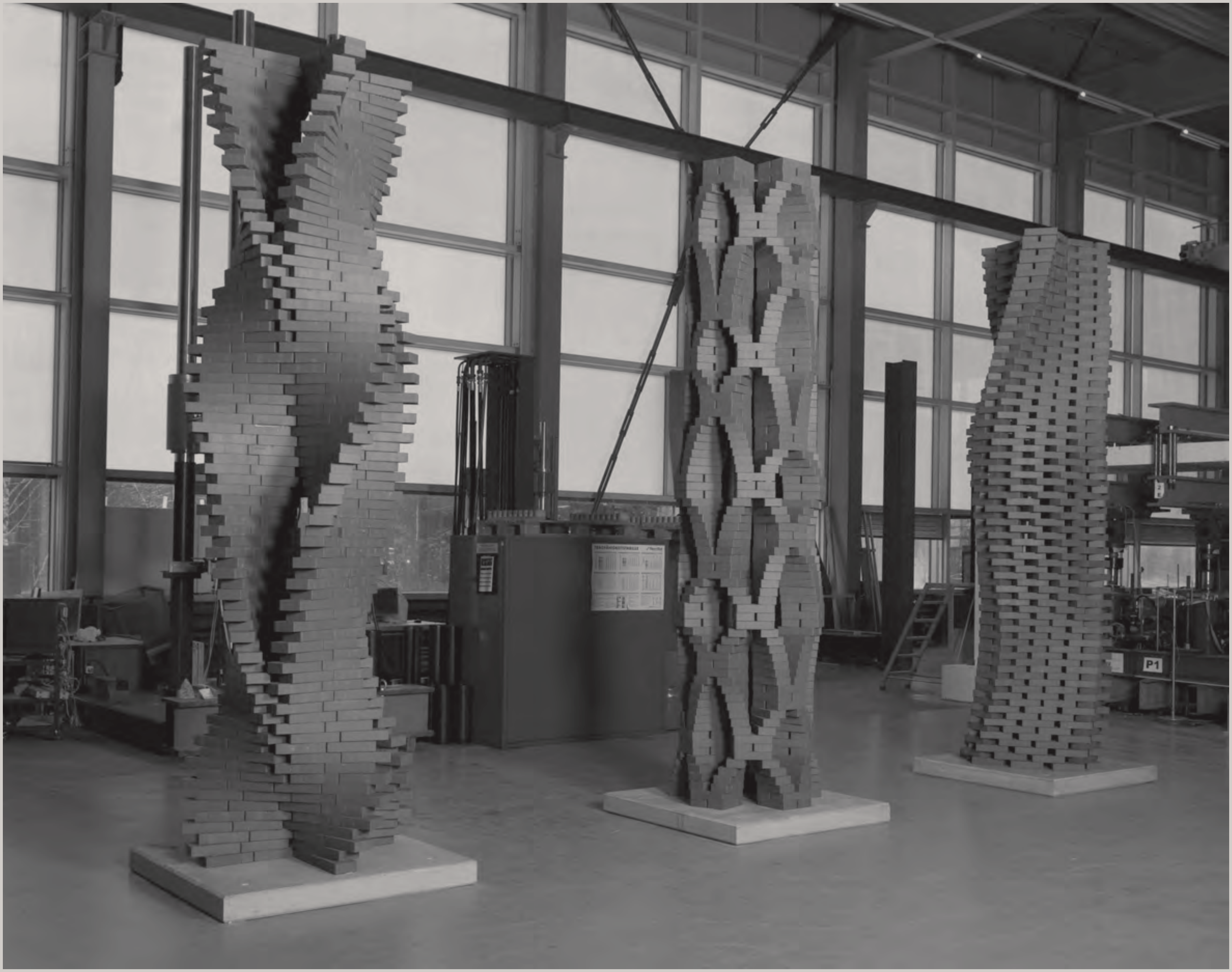
HK / Some observers are saying that one of the wonderful things about this kind of technology is, as you described it, to distribute it and use it at a low-tech level. Do you think there is a chance that your kind of work will reach further into the new orders in the developing parts of the world, where we have abundant low-craft skills actually feeding off scarce high-end digital technologies?

MK / I am interested in a low-tech and 'do-it-yourself' approach, but it's not really what we're focusing our research on. There are others who are conducting exciting and relevant research in this area. Our focus is on simple and effective technologies that affect the contemporary reality of architectural design and construction. We try to avoid being nostalgic about technology. One effective way, which is neither low-tech or high-tech, is working with generic technologies, such as industrial robots or computers. They can be easily customised to a variety of processes and are inexpensive.

HK / What is next for you then? Have you some thoughts you want to share with us about what might happen next? Making everything quicker and cheaper? Good, quick and fast, that's what they want isn't it? Which is essentially what a robot does, doesn't it?

MK / Yes, of course, we have a couple of venues that we are pursuing. But first I would like to comment on the 'good, quick and fast' attitude. It seems like a very capitalist, performance-oriented perspective on architecture. There is a risk that the whole digital fabrication topic becomes overheated in the next couple of years, similar to digital design in the 1990s, where you had all kinds of wild forms generated on the computer, rendered seductively, yet few understood how to control them and hardly anyone understood how to build them. Now, to some extent, there is a similar lack of a thorough understanding within digital fabrication.

Structural Oscillations,
Installation at the 11th Venice
Architectural Biennale 2008



The Programmed Column 2,
ETH Zurich, 2010. Elective course in
collaboration with Prof. Philippe Block.

In difference to the 1990s, stuff is being built, but it's not always understood. Although it's very unpopular, I would rather advocate for a slowing down and ask: 'Have we really understood what it means if we reconnect contemporary design and fabrication techniques to the constructive tradition of architecture?' There is a prevailing knowledge of architecture that we have lost, and a question on whether we can reconnect our professional culture to this with contemporary means without just mimicking traditional ways of building. I would argue that we should go more slowly than quickly, and we should have more in-depths discussions.

HK / That's refreshing.

MK / Regarding your question about what is next, we are, for example, interested in multi-material approaches, because hardly any building that you've seen is just made out of one material. But most of the research you see out there is basically mono-material structures including, to a large degree, our own research. Of course there's good reasons for that, since it is simpler to conceive and build such structures. But engaging with aggregation of composite structures will be a challenge. Furthermore, I think digital in-situ fabrication might become a valid alternative to prevailing modes of prefabrication. How do we bring digital fabrication processes on-site? What does it mean for the architectural design, the building process and the machine? I don't think we should conceive machines that are larger than the buildings, as some people have promoted. But we can imagine small, adaptive machines that can do digitally driven work on building sites.

HK / I used to be anti-composite material but, over the past two or three years, Neri Oxman, who is one of the other speakers, has convinced me. I always used to believe that four or five materials can build anything; but I agree with you (and her) now. Going in a different direction, do you think there is much connection between digital fabrication and sustainability?

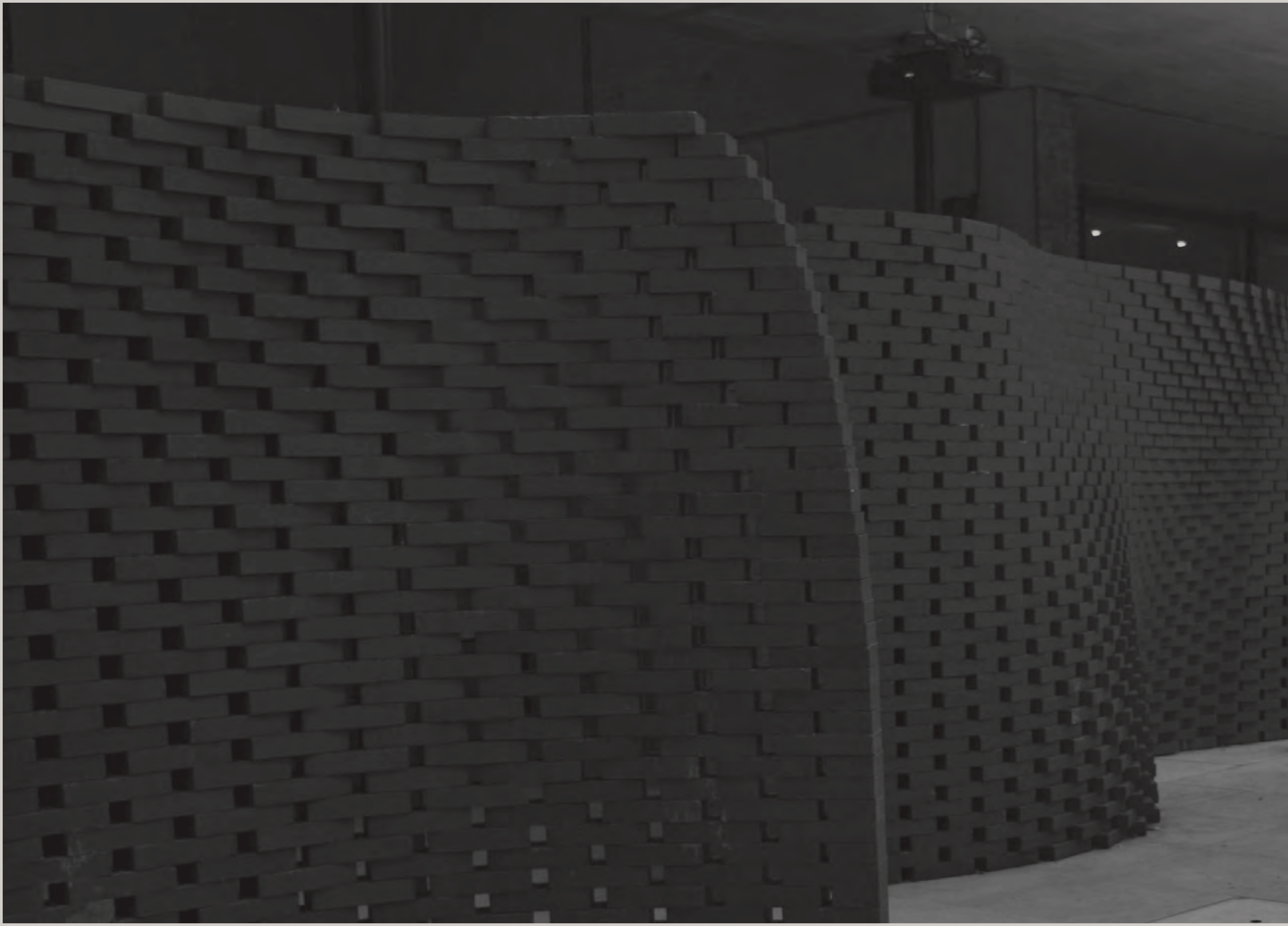
MK / If we take digital fabrication as a challenge to rethink construction from an architectural point of view, sustainability is definitely touched by these developments. It offers a tight connection between the architect and material processes. We can start to define how material becomes informed through fabrication processes and we do not have to look at fabrication processes as being predetermined, we can even conceive them ourselves if necessary. This means that we are not just browsing through the catalogue and seeing which material has which environmental effects, but we are able to define material processes ourselves.

Yet digital fabrication is no guarantee for sustainability. I think you can do very bad things in sustainable terms with digital fabrication. For example, you can mill out foam blocks in order to produce custom-shaped concrete parts. In contrast, by tapping into additive fabrication processes, which don't require any formwork to be built, you can simply place material where it is needed and eliminate waste. Again, there are very direct links but digital fabrication alone does not guarantee sustainability.

In general I am rather critical about current trends to legitimating projects primarily through sustainability. Architecture is more than the optimisation of parameters. One-dimensional attitudes of any kind are the death of architecture.

HK / I think this is very interesting. I don't know if it's a geographical thing or not, but I would speculate that, certainly in Europe and also manufacturers for China/India, are trying to connect with people like us more. Some of the best questions are coming directly from fabricators, and this is the only kind of worry I have – that if people like you don't expand and come more into construction from the kind of work you're doing, the risk we face is that others will take your place and these questions will be answered by people who are less creative. So I want to close off by encouraging you to share more of your work, not necessarily the secrets, but just the exciting work; the bits I've come across at your talk.

MK / I look forward to doing that and to a collective discovery of an emerging 'digital materiality' in architecture.



Structural Oscillations
Installation at the 11th Venice
Architectural Biennale, 2008.

MARK BURRY
MARK WEST

Mark West / During my last visit to the Sagrada Família I spent some time drawing the little school building that Gaudí made there; I thought it would be simple enough to draw, but it turned out to be extremely difficult. I found, posted inside as an exhibit, the geometric basis of the building. I found that if I drew the geometry first, then it was easy to draw the building, though impossible to do properly as a perspective-based sketch. That sort of tipped me off to the role that geometry played, not just in how Gaudí designed things or brought form to his work, but that it was actually the key to its construction as well.

Certainly there must be instructions to builders inherent within the geometry; as much as there's architectural content in the geometry. So the first question has to do with this saturation of construction information inside the geometry of Gaudí's architecture, and how he must have had his masons laying these geometries out, and how you go about doing it when you're building the church now with these different tools.

Mark Burry / Two things: he did use some of the geometries that he used exclusively for the Sagrada Família at the end of his career in earlier projects. There's evidence of hyperbolic paraboloids in very early works, and at the Colònia Güell. I think we can say that he was highly aware of their potential after the first two-thirds of his career, but if we were to compare the Casa Milà (La Pedrera) with the Sagrada Família, that's where we see a huge divergence. Casa Milà is an absolutely quintessential expression of free-form, and that free-form cost him dearly.

There's nothing written by Gaudí on this issue but my assumption is that, towards the end of his career, he must have reflected on his ongoing viability as an architect; he'd lost his good standing with the bourgeoisie and, following a period of illness which required a lengthy convalescence in the Pyrenees, I suspect that he spent a considerable amount of time on his back, wondering what was going to happen next. I think his 'revelation' would have been an instinct for geometry to become a driver, which would be consistent with the neo-Gothic nature of the Sagrada Família, which wasn't even his idea; it was something he had to pick up from the first architect, del Villar.

The Sagrada Família parish school building is a great example of the simplest use of ruled surface geometry, and what you just said is very interesting because I think his best work is effectively undrawable, even if you can sketch it it's obviously not the way to represent the building to the client or to the builder; so geometry obviously became the lingua franca for his own intellectual processes, and then the lingua franca between him and the client.

The last point to make is that we now are using reinforced concrete for some of the building and, in these situations, the geometries accommodate the reinforcement beautifully, picking up the straight lines of the doubly-ruled surfaces. So even structurally it turns out to be an ultra-efficient approach. The question underlying all of this to many is: 'Which is the real Gaudí: the Casa Milà or the Sagrada Família?'

MW / On the geometric production of the 'new columns' for the Sagrada Família's nave, with double-rotating helical star profiles and so forth; do you know of how Gaudí would have instructed his masons to cut the stones for this geometry? Would that have involved a template that would rotate, or was it done with his 1:10 models he'd give to his builders and they'd freestyle it from these?

MB / I'm not convinced that Gaudí fully understood the potential for the columns themselves as a description of life forces because there's this series of divisions that starts off as two profiles, then there are four, then eight, then 16. The reason I question this is because one column, built in the 1960s near the interior of the Passion Facade, still remains. It's the column dedicated to Barcelona in the transept, as one of the 'eight-pointed' columns. It was made by interpreting a surviving 1:25 model composed of a series of zinc profiles at metre intervals. On the model, plaster of Paris fills the space between each profile as an interpolation of the geometry. The 1960s column was conceived as an extrapolation between two templates, one at each end of the column drum and is therefore a simplification, it isn't an authentic outcome.

Around 1992 we machined a version of the same design and because every single section of the column horizontally is a combination of two profiles that are intersected, it was formed as a 'hard-coded' process, where the saw blade would move into position, follow the given curves in 2D, then move one saw blade width (which is 5.5 mm up the column axis), adjust to the profile and then cut that profile. This led to an elegant series of horizontal stripes one saw blade thick, going up the height of the columns. These are the markings that I think you've noted in your question.

So this mechanically produced column is actually the real column, as described by Gaudí's geometrical thinking. The Barcelona column of 1960 is only accurate in profile at 1-metre intervals, but in-between it's an extrapolation which isn't geometrically 'honest'. The curious thing is that you end up with a more geometrically authentic result by machining than you can do by hand. I don't know how it would be built by hand in the way I've just described; I can't imagine it being built by hand in the same way.

MW / Maybe this is also a good time to ask a question about the stone being hit by the blows of a stone-cutter. This question proposes that the church essentially has to do with suffering and redemption. The older stonework of the church has in its surface a palpable violence – the pain of the broken rock – compared to the smoothness of the perfect machine-cut pieces. I suppose even the saw-cut stones you were describing before, are not hit and broken. I'm wondering about what's lost, or how the architecture has changed in that way; not in terms of geometry but in terms of action; the presence of violent actions, with respect to the question of pain and redemption?

MB / I have to say that at no time have we specifically said that it's all about suffering, or it's about flaying and cutting. The theme of Christ's Passion has nevertheless always been behind the conversation that these columns are part of the 'death' portal. The Passion Facade is celebrating aspects of the death of Christ, ultimately leading towards redemption. So these columns have to have a certain savage aspect to them in terms of their production, and because all decisions are made as decisions among equals, they have been quite contentious. There is absolutely no expectation that any part of that surface will be the polished, smoothed outcome of a mechanical process that's perfect. The debate is on how much of the column will be flamed; a process that causes the stone surface to spall.

So, as matters currently stand, we've a mixture of surface-cutting with a saw, and flaming the surface with a blowtorch. I think that, at the end of the day, there's no difference between either of those methods and somebody on the end of a hammer and chisel; other than the fact that sweat hasn't been literally expended. But, if you looked at it from the perspective of someone who didn't know how it was made, you would look at a rough surface and be curious about its roughness, and you'd look at the other surface and wonder how long it took the person with the angle grinder to make all those marks in the surface, because that's what it looks like!

MW / There's also the absurdity of producing something by CNC router, and then sending someone to go in and hit it with a hammer afterward.

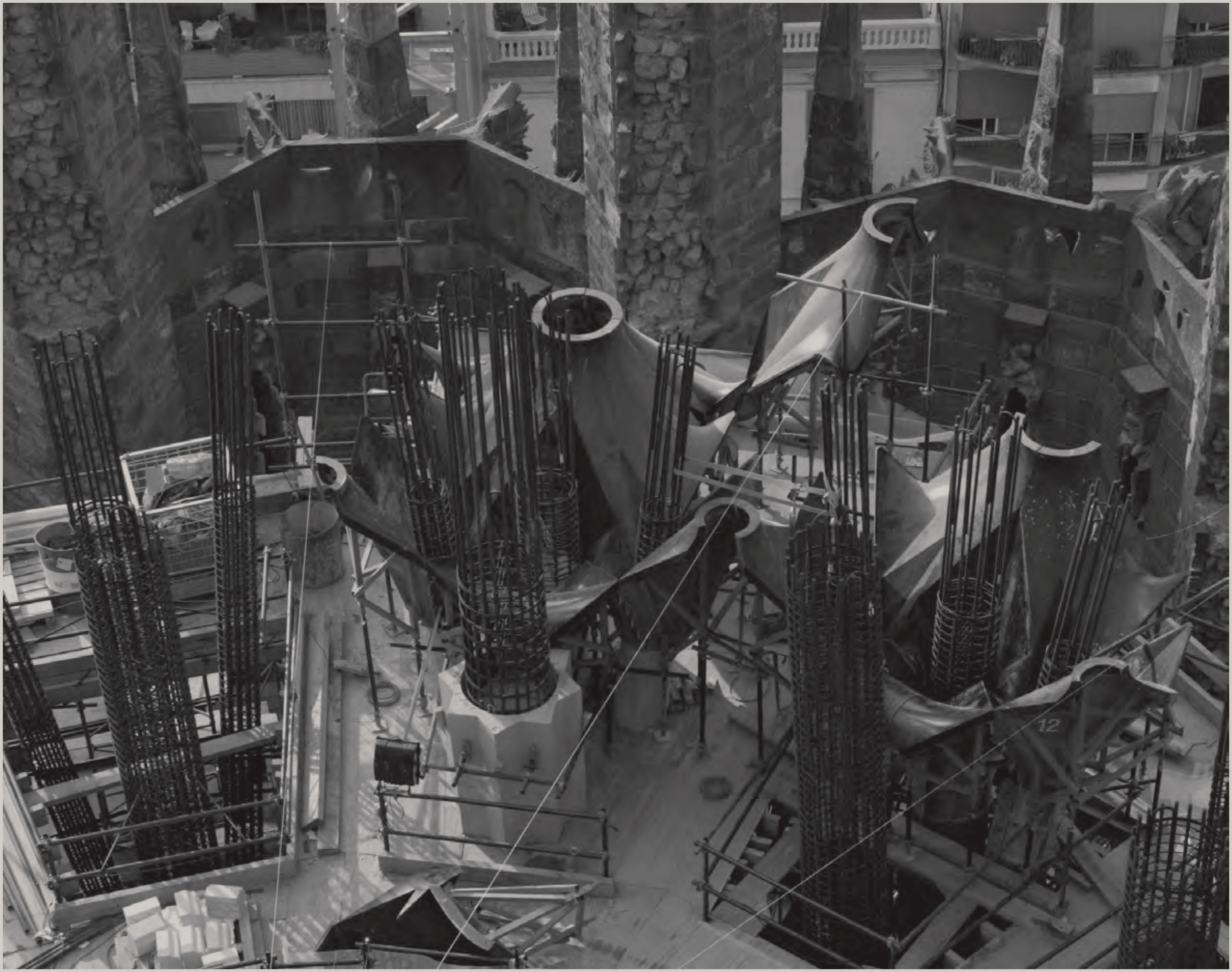
MB / Ten years ago, the only pieces of advanced technology on the mason's site in Lugo, North West Spain (the late Sr Manuel Mallo), was a telephone, disk saw and diamond wire-cutter. He invented a system using a 2D CAD package where templates would be scored on either side of the piece of stone being cut (we're talking about stone about 2 metres in each dimension). The diamond wire would come down in a straight line and the piece of stone was steered in space by a bloke at each end on a lever. As the wire came down, each would be making sure that the template would be lined with the wire, so he was able to cut a ruled surface. Sr Mallo (aged 78 then) thus had the ability to get the surface roughly cut mechanically within a centimetre of the final surface, removing 95 per cent of his labour, which, from his point of view, had been a complete waste of his time. He was very happy to just spend all his time concentrating on making these perfect, finely chiselled finishes.

MW / With the procedures you have now you must be able to get right to the surface that you want, is that correct?

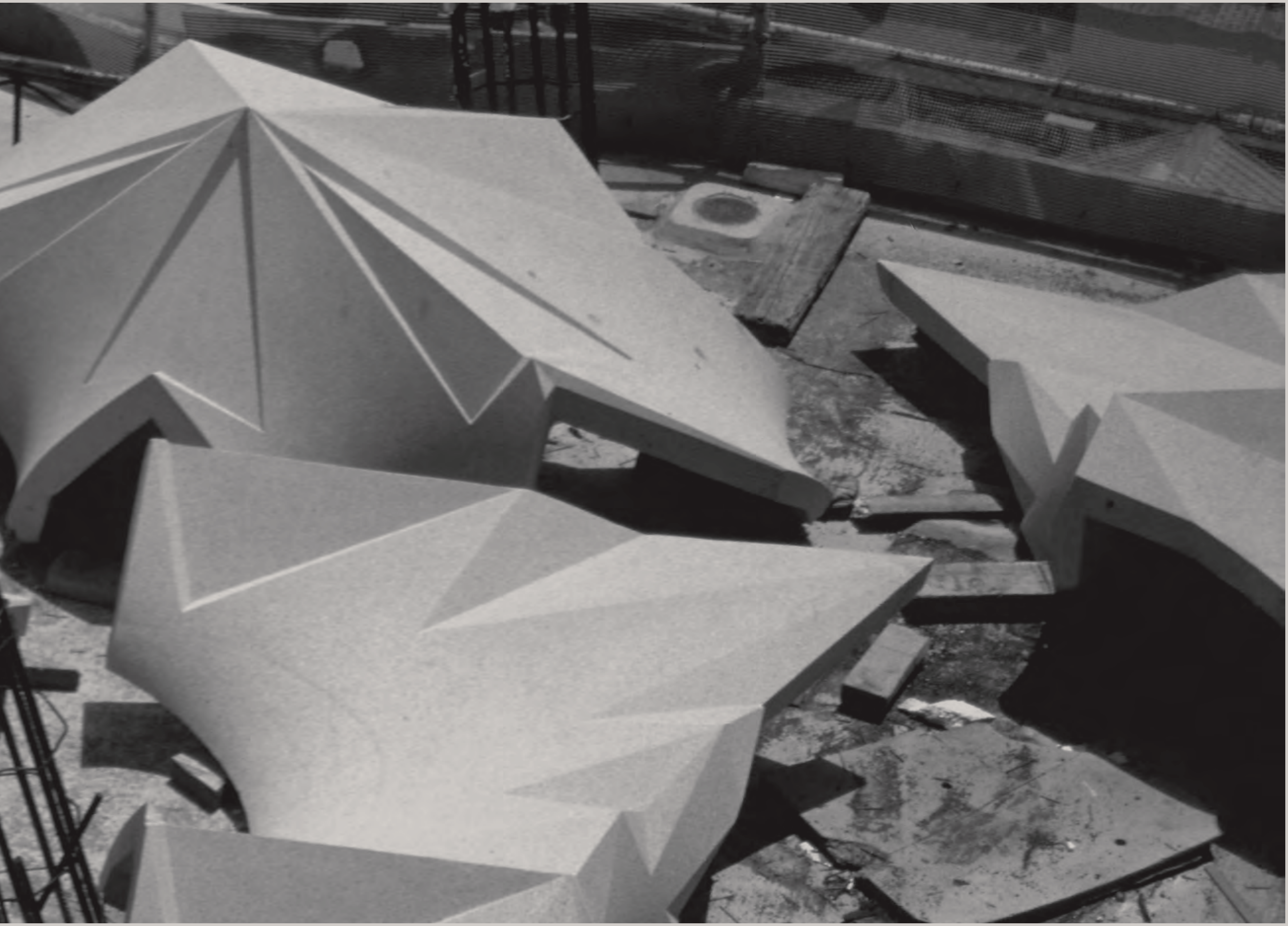
MB / Yes, and that's why the bit that I've talked about already, the dilemmas that I've just described for the Passion Facade columns, is evidence of the stonemason wanting to prove that he or she can actually give us the product finished perfectly, whether by hand or by machine, whereas we, the architects, are actually insisting on a kind of human intervention laid on top of it, despite that being an extra cost in some cases.

MW / What do you think Gaudí would have thought of those perfect surfaces?

MB / I'm always very careful when I'm asked to speculate on what Gaudí might or might not have done or thought. I'm trying to think of what he did mechanically that was perfect and I can't think of anything. I know that he has a reputation of always trying to use existing technology where possible. Apparently his refrain was 'why would you risk a novel technology doing something that you can already do well enough?' On the other hand he wasn't frightened of trying new things out. He didn't use concrete until the last year of his life, even though his major client was the first person to manufacture Portland cement decades earlier.



Fibreglass moulds ready in place for the in-situ pouring of 'artificial stone'. The moulds were made from a 1:1 plaster of Paris master.



Artificial stone components for the clerestorey window for the central nave of Gaudí's Sagrada Família, ready for installation.

But then he got to the point of the building where he could only use concrete, and so he used it on the pinnacles of the Nativity facade.

MW / Just to shift a little bit to a question about modelling: the last time I saw the model shop at the Sagrada Família I noticed that the 3D printer had entered the shop, and I'm wondering if that isn't a more congruent way of making models, now that the actual construction of the building is also being done through computer controls, or whether something is lost – what's lost and what gained and so forth?

MB / I've had two jolts to my sensibility; the first was when I asked the stonemason whether he felt cheated by having all this first stage rough stone reduction done for him, and the second was when the dust printer came out to replace the wax one. Having prototyped in wax previously, a complete novelty, the dust printer forced us to enter a new language, because it meant that the production of prototypes was returning to using the same material that Gaudí had used – gypsum plaster. So, having had a five-year flirtation with wax printing, suddenly we were back using the familiar material.

About five years ago, we had to produce a large number of prototypes for the main space where the towers in the centre join the body of the church (the Sala Creuer). It's been a really demanding project because there's only a longitudinal section of the whole church drawn by Gaudí for which the critical space above the crossing is simply hatched out; there's no real information. So there's any number of spatial configurations possible in terms of how the towers relate to one another, and how they relate to the nave. At the same time, it needs to be a serviceable space in the form of an auditorium. So, for the first time in the project, we required a large part of the building to be modelled. Now Gaudí had modelled the nave and the towers at a scale of 1:25 and at 1:10, but they are far too big for modelling the whole of the towers at the centre of the church. By using the rapid prototyping dust printers, we were able to model this area at a reduced scale of 1:100 and 1:50. To take these very delicate pieces of 1:100 and 1:50 models out of the machine, strengthen them and then assemble them into these giant models – 1.5 metres tall in some cases – is actually a very demanding task in its own way.

So that's the first answer to your question. The second answer, which is the really bad one, I feel that we're in big trouble now: I've a new research topic that I'm describing as 'visualising the unfamiliar' and, what has occurred to all of us, is that when we get to a major space like this one, the Sala Creuer above the crossing where not one single surface is flat or vertical, or horizontal in many cases; what we've found is that the renders that we do are insufficient in terms of providing a credible spatial sense of the interior. We've even gone to the trouble of 3D modelling with stereo glasses to try to get some kind of spatial effect. What's happened time and time again over the past five years is that we get approval on a set of renders. We then model the same space or component in 3D at a scale of 1:50, and we'll get approval on that, except that, time and again, we've found that the renders were in fact inadequate; so we've had to go back to the 'drawing board' a number of times. But even when you get the model to be acceptable at 1:50, you then say 'well, we'd better get a version at 1:10', at which point you find things that are wrong with the design at a design level of 1:10, which are visible at 1:25 or 1:50, but not noticeable. So one of the big dilemmas that we're facing is that it looks as if without one-to-one prototyping of unfamiliar objects and unfamiliar space; you're pretty well in the dark. That's not an individualistic observation, it's something that we all feel rather nervous about; that the facsimiles made through computer rendering, and the physical facsimiles produced through scale modelling, are not necessarily representative of the spatial experience at the human scale.

MW / Is it the spatial experience that is insufficient, or is it the actual connections between these complex parts?

MB / Well the spatial level is a kind of hunch at the moment because we haven't actually got the full spatial-surround immersion thing working in a convincing way in my view. But, at the spatial level of the human interaction with the full-size objects, including a column referred to earlier, ultimately it is the appropriate test, however unrealistic one-to-one modelling of buildings might be. The columns for the Passion Facade were prototyped at one-to-one, and were placed in their positions on site for quite some time in order to gauge reaction because it's such a controversial part of the project. We were all surprised when these giant columns emerged from the shipbuilder who made them, because they were completely different from what we'd expected, despite having had a scaled version of the same column that was about 30 cm in length. Even now, to test the stone-cutting technology, we've made a 1:5

version of the column, which has had to be supported by a specially produced steel frame, and it's become a kind of exhibited object; so a 9-metre column at 1:5 is actually getting close to human height. When you look at it, it's still a completely different spatial experience to when you're standing next to a column at a full size.

There's one thing that I will probably show at the FABRICATE conference, which is a rainwater hopper. It couldn't be a more simple thing; it collects the rain from the roof and guides it down a pipe, but there have been 17 versions of it. It wasn't because each time we made a version a better idea came up, it was because each version was designed, rendered, printed; then the printed object, which would be the size of a tea cup or smaller, was clearly not what we were wanting it to be and it would have to be reworked. So that was when we first became aware that renders were just impressions, and not actually that useful – and it's quite worrying!

MW / Have you tried changing the optics in the model so that you can optically make yourself small in the space?

MB / I'm very careful within the perspective view and set the lens to 50 mm, just to try and match human spatial perception as closely as we can. We did play around with our university's immersion facility with 3D stereo for a while too, to see whether that made a difference, and it does; you get a different kind of experience, but it's still not enough. So the bottom line is that we have to prototype, but I'm suspecting that, without a one-to-one prototype of unfamiliar objects or unfamiliar spaces, we are probably always going to be at least slightly surprised by the outcome. Obviously we haven't prototyped the space above the crossing at one-to-one – it is 25 metres tall and 25 metres across, but I just received a photograph from the stonemason who is making those pieces, and what they've done is assemble the first three courses of objects; so a human being is about half their assembled height. I got a severe jolt when I realised just how big it's going to be, and that was looking at the exterior. Because one is so used to having the design gliding around on your large monitor you get a familiarity with it, which is completely out of sync with its scale in reality I believe.

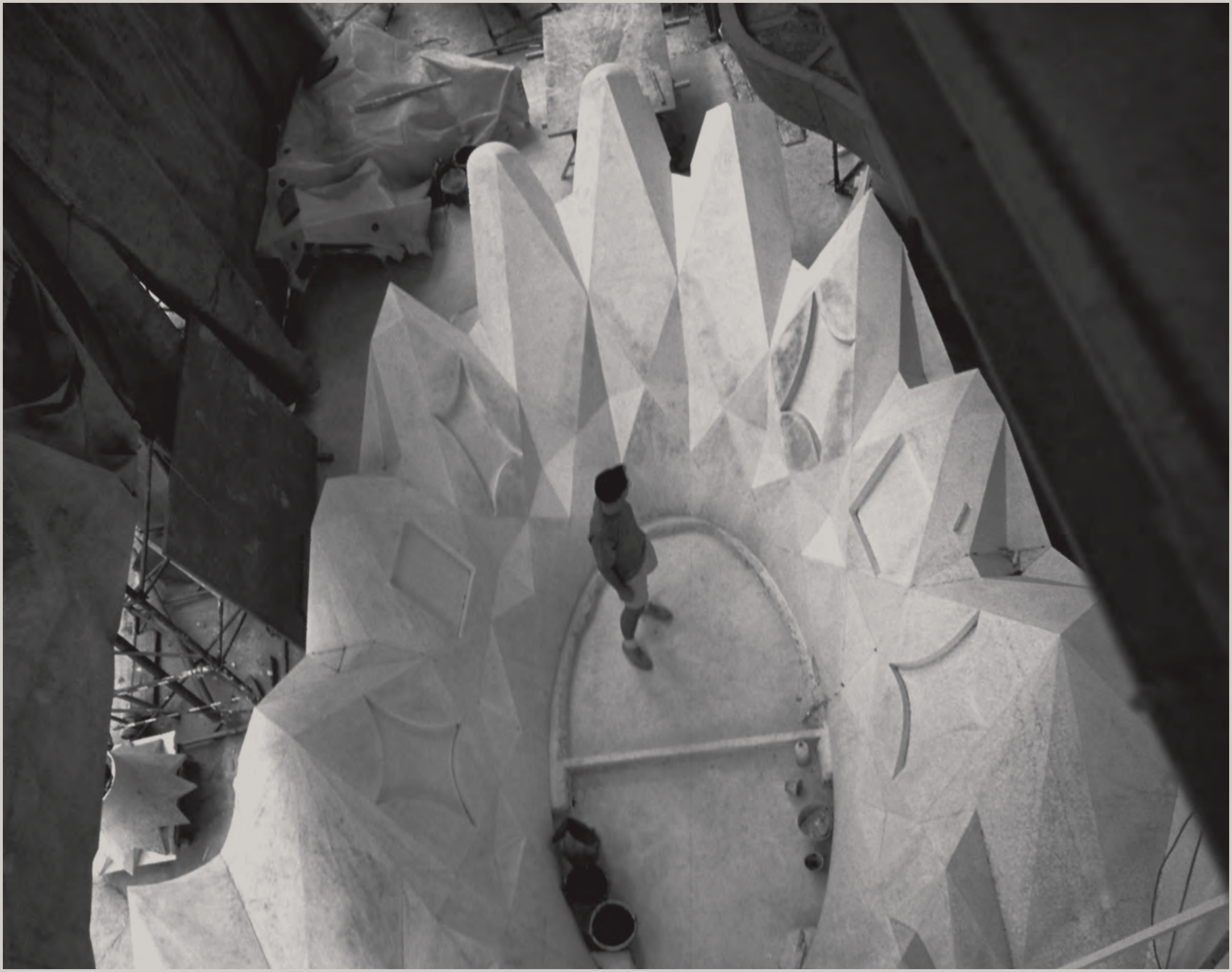
MW / I suppose that's a regular part of doing architecture with a building – that there's always a surprise when you see the thing in its full size?

MB / Yes, but what I suspect is that we're guided by our sense of familiarity. At least that's my experience; as an architect, I have been surprised by subtle lighting effects that I hadn't anticipated, but I was never really surprised by a spatial outcome in the way that I have on the Sagrada Família project. So the only thing I can put it down to is the fact that for the Sagrada Família, we're always producing unfamiliar spaces or situations, so your mind has difficulty making the extrapolation to other experiences that are similar.

MW / If we leave Gaudí for a moment, perhaps I can ask you a question related to the unfinished, partially cut, stone pieces you show in some of your photographs. These are stunning things: I'd never seen anything quite like it; the combination between the raw quarried stone and then the extraordinary milled surface. I'm wondering whether those things have struck you as a discovery within the work on the church? They seem to indicate another architectural language that is made possible by these machines.

MB / Well the simple answer is yes. The issue that I'm grappling with at the moment is that, last week, I was on the site of the stonemason, Jordi Barbany, just outside Barcelona where they're now undertaking the complicated part of the 'crestaria' (crenelated gable) above the columns for the Passion Facade.

I've got some extraordinary photographs of a new set of processes around hollowing-out stone elements to receive concrete. The savagery in which the stone has been mechanically reduced by fairly clumsy processes in order to allow the robot router to finish it off was on show. On site there was a big machine that they've just purchased. I think it was from the 1950s: it's Hungarian and it's painted bright blue; it's huge. It's has this core bit, and they've bought it so they can do the extraction, such as when they have to sculpt voids for the reinforcement to go in to make the horizontal cantilevered or bridging elements strong enough. And I was reminded, watching this very powerful machine that was making, relatively quickly, a series of 75-cm diameter core extractions (nevertheless, it was taking half an hour for each one of them) that it doesn't matter how much we automate all of this, it's still going to be expensive building out of stone, certainly in terms of the time taken. So we may need to try to find other clumsier process to work with stone because, certainly from a tectonic level, a piece of half-finished stone



Sagrada Família, 1:1 model of Gaudí's design for the clerestorey window located above the central nave.

used appropriately has appeal similar to that of yours which you've expressed about the columns in the Colònia Güell church.

MW / Those are my favourites I think.

MB / Are you aware that they're actually naturally occurring basalt prisms?

MW / Well yes, except there was evidently some instruction about making the capitals because they are smashed up to be sort of like capitals – but not.

MB / Yes, and the bottoms of the columns have great chunks taken out because Gaudí thought they were over-structured, so he asked the stonemasons to do it, and the story goes that Gaudí offered to stand underneath while the stonemason did it as a show of confidence that it wasn't going to fall on his head.

MW / Although we know how to use these tools so we can execute with the tools as known, the 'misuse' of a tool, we might say, is where new ideas or other possibilities exist, so how else might digitised production be used? Once you digitise production, there's an expectation of a perfect rendering of a 3D space design into material reality. But it seems like if you 'misuse' the tool, or didn't use it all the way, or let other things slip in or slip off in the process, that you would have the equivalent of those unfinished stone pieces somehow.

MB / Maybe an answer to your question is that, in my view, it's absolutely essential for the architect to be fully engaged with the process. If we took the example of a large UK practice (who shall remain nameless), their approach to a perfect outcome is by disconnecting the fabrication aspects from the design office as much as possible to limit liability. Commercially sensible perhaps, but if you do that you miss the opportunity of serendipitous discovery. The Sagrada Família project team is organised in such a way that everybody is in the team, even the contracting organisations outside effectively become part of the family, at no point are you ever remote from the physical processes involved in building. So the whole point of our visit to the site (from Australia) every six weeks is to help ensure that we can be physically present to see progress and understand its design significance. I think when I look at conventional jobs, there's no reason for an architect to go up to a stonemason's quarry to see how they're getting on because you'll see what you already know; in a conventional contract you are not that interested in how it's achieved, you just want the thing to be there on time with the right level of finish and at the right cost. But, by taking that attitude, you miss out on the opportunity of seeing what you might do as a creative divergence from conventional practice through experimenting with a tool. I mean you're only misusing the tool from the toolmaker's point of view, you're actually exploiting the tool from a designer's perspective if you're using it differently from how it might have been envisaged.

MW / It strikes me that there are probably many architects who love the idea of somehow printing their building, because it would mean they don't have to go into that scary realm of the construction site; it's seen as something to be avoided by many architects and there's an attraction to the idea of complete control by simply printing a building; which would hot-wire around all of the stuff that you're talking about now.

MB / I've a PhD student who's just finishing up who has been collaborating with Enrico Dini and Rupert Soar. The main issue to me about these printed buildings is that from a tectonic point of view they present the most extraordinary challenges in terms of the integration of services and structure. So I think there is rhetoric, and as usual it's a magazine-driven rhetorical ideal, but the reality is that technological innovations are now required to integrate services and structure, and these are huge. If the architect won't engage with that, then somebody else will, and that will be to architecture's long-term disadvantage in my view.

PHILIP BEESLEY
MICHAEL STACEY

Michael Stacey / Phillip, as you well know, back in 2004 I curated the Digital Fabricators Exhibition, and you kindly hosted the North American stage in the Cambridge Gallery, the first ever exhibition there, and Bob Sheil's work with his colleagues, sixteen*(makers), was included. Do you think it's significant that the 2011 conference drops the word 'Digital' and is just called 'FABRICATE'?

Philip Beesley / I do see significance in that. The implication for me is that specialised craft rooted in material manipulation is a key for quality in the field of building today, while the ubiquity of the computing medium is something that could be taken for granted. I don't completely agree, because there are a myriad of issues surrounding digital tools, but it might be well to uncouple the term 'digital' from 'fabrication', and allow each its own forum, rather than focusing (as we did many years ago now) on the novelty that made digital practice coupled to fabrication seem innovative. 'Fabrication', by stripping away the 'digital' term, opens 'fabricare', with existential and poetic implications of that eternal term. History and theory come to the fore in this gathering, alongside technique and craft.

MS / Interesting response, Phillip, because I think people have been encouraged back to the workshop, but I am concerned that today there are too many, essentially similar, parametric projects, and some of the papers submitted for the conference really reflected this, trumpeting the parametric tools, rather than making inventive architecture. It's actually less inventive than architecture from almost any other era, and they're not engaging in the realisation, and I think that part of the field has already collapsed, which is perhaps a bit negative of me to say.

PB / Certain languages in parametric design appear generic: Platonic waves that ripple out, organised in gradients, perhaps salted with certain variants that appear like viruses to interrupt the field. Random functions create difference wilfully, seeming to correspond to the tutorials that are embedded in next-generation software. A kind voice might say this reflects extraordinary progress made in skilling up a generation of designers. Yet, along with emergence of these skills, there also comes a kind of exhaustion: languages sometimes reveal themselves to be static, disappointing, when the concrete examples replace the visionary impressions that preceded them. But I'd like to see that as a healthy thing. My Darwinian hat sees this as a large project where waste and excess inevitably boil off. The rather abject state of Dubai might suggest these tools are sometimes playing uncritically, but that comes with any experimental territory.

MS / That's my concern; the uncritical use of such tools. Although you could also say that our profession has been quite slow to adopt building information models, as a better mode of collaboration. But before you can answer that, I'd like to move onto an earlier conversation we had in the summer; you suggested maybe that a future version of a BIM tool could accommodate ambivalence and improvisation; could you say more about that idea?

PB / Ambivalence can be an enabling term. I move back and forth between hard-core measurement and performance testing and, on the other hand, open, rash speculation akin to lighting matches with tinder. I wonder whether design tools might include a variable focus that invites both impression and precise analysis, akin to drawing with charcoal alternating with silverpoint. When I speak about ambivalence, I'm thinking of designers using new tools and practices to meet the challenges of our day, however unspeakably grave those might be on bad days and however inspiring and playful they might seem on good days. I want to move back and forth between optimism and pessimism as a designer. I'm trying to find a kind of human experience grounded in my own body and feelings and rooted in motivation for changing the world constructively.

I do wonder if the monster of BIM software might be improved with integrative tools for conscious play. Many of my students and colleagues are worried about how management-oriented BIM tools are influencing design. BIM tools might imply profoundly negative clerical work. There is a risk of these tools creating sub-classes of desk workers prevented from working intuitively, obligated to punch in specifications and hyperlinks to catalogue sources. Its power for control and administrative depth is clear but can BIM be a freely creative tool?

MS / On one level your description terrifies, the practice of architecture reduced to people choosing from the existing and choosing from the manufacturers who insist on talking about solutions without ever asking what the problem might be. I actually quite enjoy writing a specification because I find it a way of thinking about architecture, but the old Skidmore, Owens & Merrill model, which had a separate floor of specification writers, I think is just a waste of human endeavour and is wrong. The key question here is how one creates very strong and direct human relationships with the people that actually make things. I saw a lecture last night here in Nottingham where a London-based architects' practice described working directly with industry; they were using parametric tools, but the workshop relationship was direct, perhaps in a way that you could have seen in many generations. So I do worry that a very static view of a BIM is an institutionalisation; I almost want to say a set of malpractices, rather than a set of best practice within our own industry. I think the relationships within sixteen*(makers), for instance, is a much more productive and interesting possibility because it steps out of the conventional structure of the fabricator, of the architect and the academic, and looks for something a lot more fluid and interesting.

PB / Returning to the question of ambivalence, we've just lurched in our conversation – we started with an almost despairing sense of the sameness, reacting to trivial qualities of sine waves and gradients characterising some parametric design today. We've touched on integrated building information modelling, implying a stultifying mass of static cataloguing, a contrary of agile play. If that practice doesn't promise opportunity, then what might we offer? A kind of agile substance is implicit in your question. I admire collaborative practices where people have profound grounding in certain crafts, while at the same time they have the confidence to act as generalists. Lateral play – specialised languages transferring into new hybrids – marks that kind of work. When we look at the architectural practice sixteen*(makers), we have an example of individuals in specialised silos that have the ability to do steel manufacturing with advanced craft in that specific discipline; side-stepping to another silo, ability in computational simulation with formidable craft; then to yet another, performance based scripting. 'Emergent' design has teeth in this picture.

MS / I think the simple starting point is that, as architects, we shouldn't be embarrassed about discussing our own skill. I think the twentieth century was almost burdened with architects who said they were only generalists and they weren't good in mobilising their own skill, or mobilising the skill of others. I think that's what interests me in fabrication, is that exchange, or a dialogue between a group of people, all of whom know that they actually have very relevant skills. That's when I think the exchange becomes exciting; because you are building with them a whole set of positives, to me that's part of what your body of work eloquently demonstrates.

PB / It's a very curious question about how unskilled things seem to play so readily in architectural disciplines. The question of individual skill and the fostering of craft is something that any musician would take for granted, because that culture is rooted in the rigours of language; sound exposes its technical qualities immediately to the limbic quarters of human perception. Perhaps in that medium we take facility for granted. But perhaps, before arguing for craft, we could take the other side of the coin: did you take macramé in your art class in school?

MS / I did yes and I can knit as well.

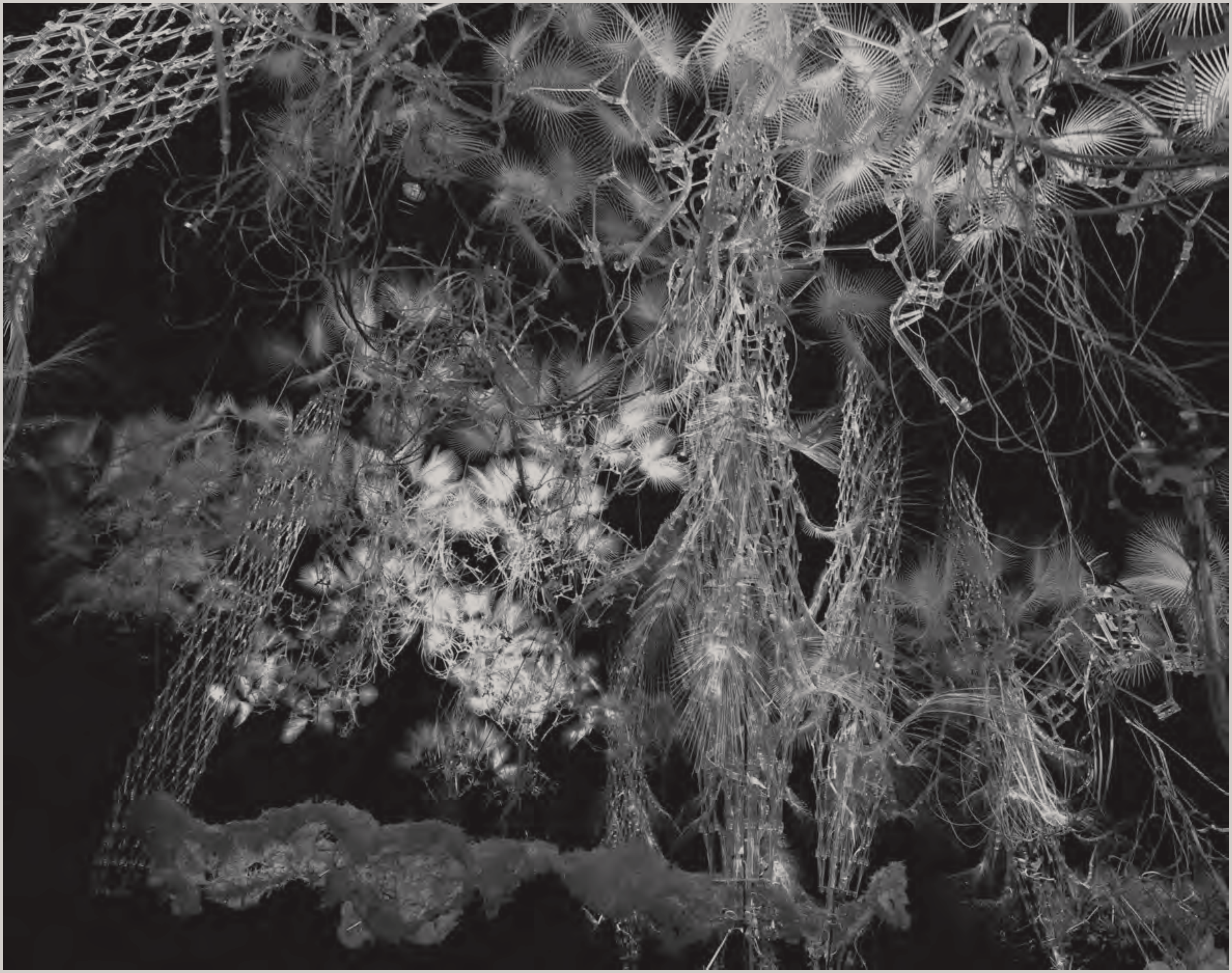
PB / The enabling qualities of physical experience are fundamental to my view of architectural creativity. But physicality isn't automatically inspiring. It can speak for a kind of dreadful silence, a kind of forlorn, blind quality of intimacy as well. There is an implied silence of the individual thing moving again and again interminably.

After a brief period of enthusiasm for the craft of macramé, the practice of decorative knotting, the overwhelming labour and slow progress of that private craft put me off. But yes, with caution, let me suggest fabrication and material embodiment offers a fundamental start to my version of design education. Would you go that far? What would be the first steps in the first year for a designer?

MS / Well here we have another complete conversation that we could have Philip. The thing I feel strongly is that there has been a sort of false dichotomy between the intellect and the hands, whereas your installations demonstrate a holistic approach very well. To discuss your installations, you need to discuss some of the making, some of the philosophy. I think there's too much architecture where it's neither built well, nor is it a constructed line of thought, to use Sverre Fehn's phrase.

I've always found that it's in the physical where ideas become evident and real to everybody, that's probably why I like workshops and also the power of the mock-up and the prototype. I've gone to appointment meetings with samples, and the committee have looked at me quite strangely. Sometimes it works and sometimes it doesn't, not to presume what the project was going to be made of...

Protocells in Filter Field
Hylozoic Soil: Méduse Field,
'Mois-Multi Festival', Centre Méduse,
Quebec City, 2010.



Hylozoic Soil: Méduse Field,
'Mois-Multi Festival', Centre Méduse,
Quebec City, 2010.

PB / I can agree, but I wonder whether there is a risk of this insistence on materiality being mistaken for something negative, an earnest and stultifying quality.

MS / That is a bit of a misunderstanding. I was actually going to ask you, and maybe we should store this, whether we could describe architecture as a collective craft, because your earlier comment sounded very much like we were knitting on our own, rather than quilting, to use James Timberlake's analogy.

PB / Yes. But this tangent might imply that the collective craft and physical embodiment risk a kind of hair-shirt architecture. To counter that we could point to some of the qualities that come of this sensibility. I'm finding myself focusing on failure and the outer edges of performance, where things diffuse and dissolve and collapse. I'm finding that material manipulation is an effective conceptual link that fosters experiment. Instability, or sources of irritation catalysing design spaces might offer performance akin to hiccupping or convulsing, a link into temporal performance. Being able to wind up a piece of sheet metal or plastic right to the very outer edge, past its performance, fosters a grasp of what it can actually do. This kind of design space welcomes dissolution and disorientation.

MS / I think it's almost essential that we give back to the students the opportunity to fail. Often that can be in the physical construction, as long as they understand what's happened, because, I don't know about Canada, but in British education, absolute certainty of success has been so ground into the current generation, they want to know whether they've passed the module before they've even started. So you have to feed the space back in to create the experimentation, and then once that's there, I feel that they become like people from anytime. I think, as professional architects, we have an interesting dilemma that we might engage in experimental processes, and yet we might have finite budgets and finite delivery dates, and so we have to almost somersault from the experimental to the certain. We had exactly that on the Nottingham house we built for the Solar Decathlon 2010 competition in Madrid, which also reminds me of your earlier comment; I think sustainability has been set back by the sort of hair-short, dour, desperate duck-and-cover approach. If we take an analogy from the Slow Food movement, it should be deeply enjoyable, and the process should be enjoyable for all of the participants. It's how we sustain ourselves and future generations, so that we're not making sacrifices to sustainability.

One of the terms you used was efficiency. I think material efficiency is incredibly important, liberating and dynamic. But too much of the discussion about too much architecture is simply about efficiency, whereas if we take the creation of a home, for example, there's so many more issues that are actually much more interesting than whether a particular solar panel is specified and whether it's 83 per cent efficient or not. It is more important whether the technology is used and appropriated. I know it's some people's role to measure, but it's almost the least interesting quality, and in some areas of architecture, the technocratic discussion just totally dominates.

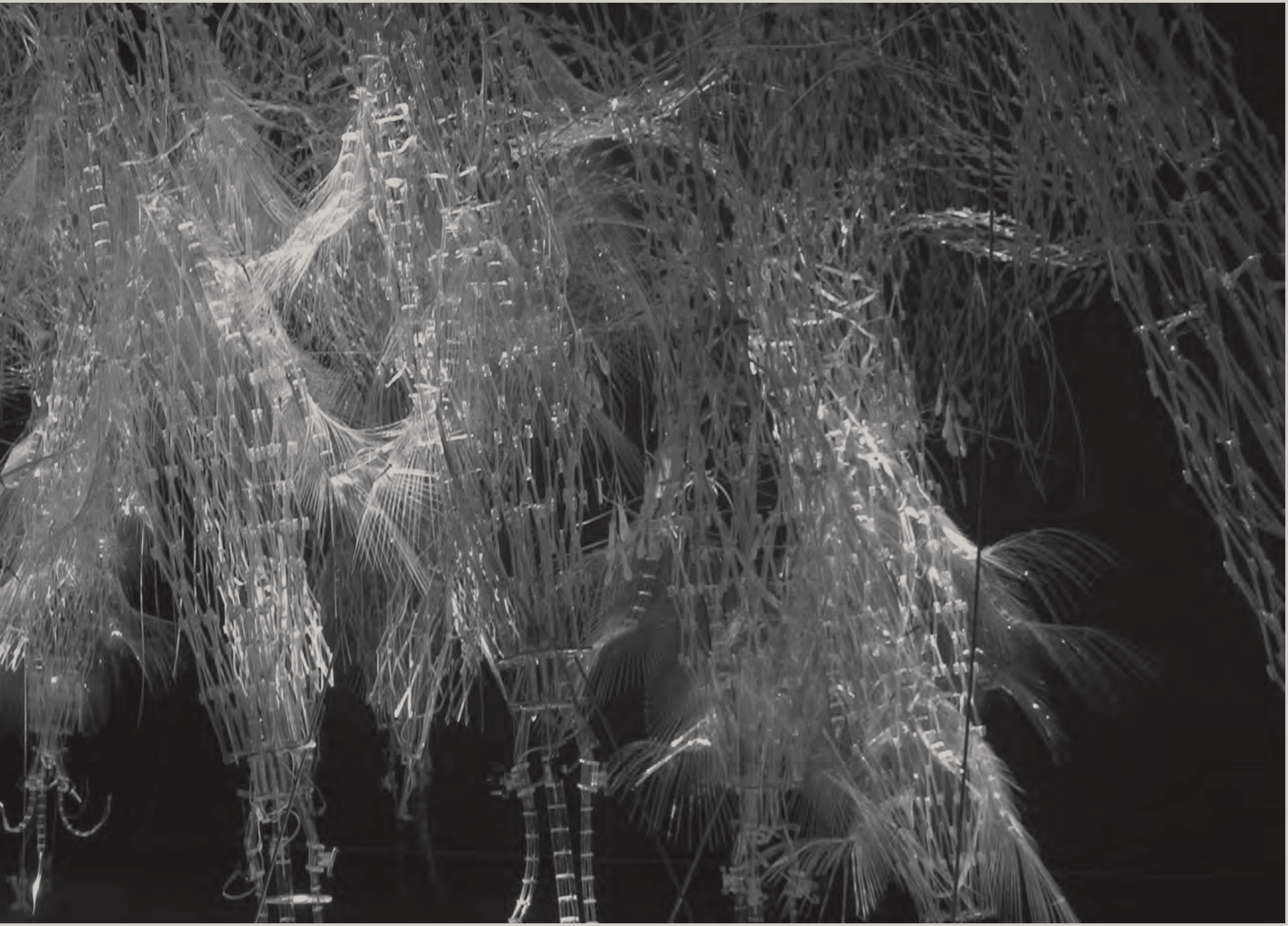
Just going back several steps, I think that understanding the past, and understanding what humankind has done through time, is actually a means of being radical, and not conservative. It's actually how one seeks the radical edge.

In that sense, I want to come back to your own body of work, because on one level I understand some of your installations to be a metaphor for healing the world; am I being too simplistic Phillip?

PB / Well, no, you're not being too simple. I'd be nervous about saying 'yes this is about healing the world', because everyone in the room might take a step back! But I wonder whether such an earnest term might be grounded both in radical delirious experiment and at the same time in fundamental human existence, anchored in a sense of the deepest history. I'd like to think so.

In the work that's in Venice right now, one strain is rooted in origins. You and I have often spoken about my encounter with blood deposits that lay under the north gate of the city of Rome. I learned that those corresponded to thousands of blood deposits and substitution burials running throughout building foundations. That archaic space seemed to offer almost unspeakable abject fragility, rounding the act of building the city into the earth.

It had a resonance with the sense of trying to create something direct and living, rooted in the soil and spreading out into the realm of agriculture and, further, into a sense of general stewardship in creating, earning the ground. I think this sensibility of trying to grasp space and ground as an active design space is an absolutely current sense. Air, water, earth and rock have vital and tangible qualities. This seems a valuable way of approaching the environment.



Hylozoic Soil: Méduse Field,
Musée des Beaux-Arts,
Montreal, Quebec, 2007.

Perhaps that implies an opposite paradigm to a modern idea where we're independent figures, strong, full of liberty, acting in a void; the void left by killing any stuffy sentiment about God and organised institutions. That empty space might be felt as a kind of liberating openness for human action. But that sensibility, which proudly eliminated history from architectural education and practice, also resulted in carelessness. In my quarter, that meant you could just throw your crap out of the back of your cottage and the wood will absorb it. The vengeance of that way of working is upon us. Making space tangible, where we can literally feel the impact of our actions, has such incredible urgency for us as architects. That to me implies a continuum between cultural history and material measurement and the material efficiency that you were speaking of before. I love the sense that we can work with those kind of realms. I think that the kind of mythic presence that they can have offers an enabling state-of-mind. Plastic, rock, paper, water and soil are not neutral; every one of them has a presence that we can manipulate. We can access the archaic when we approach them.

MS / Would you call that a gentle accessing of meaning? For example, the architecture of the 1960s was very rhetorical – often the writing was fantastic but the physical experience, of housing in particular, was appalling, so there was a gap between the claims and the reality. What I heard you describe was a sort of rootedness, and I want to use the word 'gentle', but it is meaningful; maybe if I was writing a paper I would sit for an afternoon and think about that. The other thing I heard is an understanding of technology in a transparent way, so it's not important whether the Egyptians or Romans invented concrete, or it's not important that you're perhaps using the latest of technology to make your installations, but you're actually seeking immutable qualities that communicate past the modern project as it's articulated by a particular school. I should ask you whether you're alluding to French philosophy because I can hear philosophers implicit in your comments, and perhaps I should ask you to be a bit more specific; but already I've packed in about six thoughts into that reply.

PB / I could start with your 'gentle' comment and maybe go for the jugular: there's a risk of a tangent of our conversation as invoking a kind of happy clan of harmonious villagers. But the kind of materiality that we're talking about has a kind of roaring visceral side that is not obedient. The forces that are embedded in the concrete encounters that underscore this conversation are by turns wild, disruptive, and sometimes enabling.

MS / No, I take that more to be a reference to Ruskin and Morris, and a certain sort of medievalism; it was hardly helpful as it wasn't altogether the reality of what they did.

PB / Together with Ruskin I think it's quite justified to speak about Georges Bataille and maybe even Hermann Nitsch as agreeing with this tangent. Invoking them, a tangent of design leaves control; rather, the energies that are being worked with can eviscerate the body and disorient it. Material parts of what they speak about are rooted in fertility and vitality. That might help close a loop, which might otherwise have been rather static in its earnestness and thoroughness. I prefer a group of twentieth century thinkers focused on vitalism to the kind of displacement that sometimes shows itself in continental philosophy.

MS / So much discourse is directly technophobic isn't it, as if the inventions of human kind are a problem, which in part they are, but they also bring us comfort and joy.

PB / Yes. I was heartened by a curious gathering recently at the ACADIA conference at Cooper Union. A group rooted in French philosophy and history were sitting alongside parametrically grounded designers focused on computation. There were two large assembled camps with enough depth that they could start shouting at each other. It seemed to be a sense of a next generation of emerging thought. Picture Buckminster Fuller's transcendental structures, and then the mongrel monster that Donna Haraway would concoct with her flesh and robot amalgam; picture them sitting side-by-side and speaking to each other; it was really quite encouraging to see how hybrid language might be projecting forth. Amidst amazing amounts of noise, the occasion spoke of a re-tracing of postmodernism in an optimistic sense of that word, regaining lyricism and poetry and embodiment. This joined to the intellectual pursuits to the interrogation of power and the possibility of consciousness and reflection. There is a sense that the ethical qualities of being able to manipulate life might allow a new generation of postmodernism to emerge.

MS / The two things that I definitely agree with there: I think one of the problems of architecture is that postmodernism collapsed in on itself as a sort of surface imagery, I almost want to use the word 'style', which is a word I typically avoid in architecture. I think it's one of the problems of contemporary architecture that postmodernism as a chain of thought wasn't profoundly sustained, it collapsed. So it's interesting if you're saying that within ACADIA that becomes of interest again. But the other word that you used was 'power', and one of the things that I've been thinking about the way that sustainability is articulated, it's that the politics of the world is not discussed, when actually it's fundamental to human ecology. I think there's been a false presentation of sustainability, as if we can all do it without having a discussion about how we manage resources, and to build we need resources. I think there's a political dimension to the discussion that has been uncomfortably shuffled underneath the carpet.

PB / When I hear you speaking about power, it makes me think about the agency of an architect, rooted in building. I think about widely polarised positions: on the one hand, I might think about the confidence that I see in some of your own work. I think about some of the early component-based envelope systems that you developed for example, with direct engagement in industry, so that integrated building systems can be used and played lyrically. Polarised against that, I think of the picture of a weak architecture of Ignacio de Solà-Morales, who claimed you could hardly participate in the world meaningfully; the only thing architecture could do [according to him] would be to have a weakly resonant frame where you hover at the edge of things. Perhaps, in that view, you could create ornament that can wrap around whatever is going to play at the centre. The centre would be controlled utterly by others. Those are two opposite pictures of agency and participation.

Perhaps, some new tools and thorough involvement in new materials makes possible exquisite subtlety, and perhaps those might reconcile those two positions. For example, materials can be wound up so that they're sensitive, so that they can tremble and so that they can act as environmental registers in an envelope.

With direct manufacturing the prototype can go through generous cycles of development, and competence can emerge, qualifying systems for application at a generate public scale. New generations of architectural skins and surfaces can offer qualities of sensitive and responsive phenomena. I'm trying to point to the possibility of new generations of fabrication offering some lyrical qualities.

I imagine detailing systems that might capture temporal and dynamic qualities, speaking of flux, exchange and flow. I imagine this entering the iconography of public institutions, articulating public power. I would love to explore this in terms of ornamental systems integrated with construction component systems, speaking of emplacement.

MS / Okay, Phillip, to me that sound like it could be a really inventive architecture and that's one of the qualities that I enjoy. I worry about the sort of vaguely innovative architecture that is so common, let's not dwell on that though. I think my final question is; what are you designing now? What's next? What's the optimist doing at the moment?

PB / I'm trying to move into emotional kinetic patterns in the responsive fabrications that have been in the studio this past year. Some of those first layers of kinetic response are really dreadful. They are plagued with similar qualities to the parametric exercises that we were criticising earlier, strikingly predictable and rigid patterns The risk of this is creating a new generation of B.F Skinner's horrific mid-century experiments; the Skinner Box, where a child would grow and be happy in a Pavlovian container. But I'm trying to anticipate and find patterns of response that can show care about their occupants; trying to achieve qualities of mutual relationships. The opportunity opens a lovely kind of play and invention.

NERI OXMAN
SEAN HANNA

Sean Hanna / It's been a little while since we've spoken. Six years isn't really a very long time, but do you think, because it's such a rapidly changing industry that there have been major changes in the state of the art in that time?

Neri Oxman / Changes in industry's state-of-the-art have been mostly incremental, that is to say non-disruptive innovations that have made more efficient than effective design protocols as we have know them since the digital revolution.

I think that has been the case for digital technologies that have initially emerged to serve the designer-architect in his or her search for the generation of form, but, in terms of making, I think there has been way more promises than proof for an actual paradigmatic shift. Today, however, I believe we're definitely on the cusp of a quiet revolution.

SH / So you think it's definitely changing now though? This is a cusp as far as you see it – the new paradigm shift.

NO / I think so, although it's unclear to me when that shift might make itself visible, world-changing. Such a shift, I think, is much more of a conceptual shift than an overnight amendment in production protocols; unlike, say, the invention of print by Gutenberg, or the invention of other disruptive technologies such as the digital camera, that completely changed the way we think about the written text or visual images. I think this is much more of a quiet revolution because it also requests an intellectual framework to go along with it to think about the origins of design and form.

SH / You've used the words 'production protocol', but then talked about design itself. This is interesting because classically I suppose you'd have people making a distinction between the design phase and the production phase as something completely separate. From what I see of your work, I think we both agree that these technologies are not just about production anymore, and that they are not just a means, but do have a major impact on what most would consider to be the design phase as well.

NO / Absolutely. It's been a long-awaited dream of mine to see fabrication enter the very first stages of the design process. Fabrication is slowly shifting from a state of being simply a production protocol, a service station for the designer to gather knowledge, and slowly moving to a point where it can have generative significance. My vision would be that fabrication would become part of the conceptual prophecy of the generation of form and considered very early in the design process.

SH / There are several really interesting things you've mentioned. The first, I think, is that if we're talking about a design process that involves fabrication right up-front, so that you can reflect on it, which is at one level what we're talking about; you're saying that 'rapid prototyping' is the wrong set of words to describe that. I always have a problem with 'parametric' design being too common a word and one that doesn't really describe what I would consider to be the most important part of the process, which is actually crafting the associations within the model, rather than the tweaking of the parameters that really only comes after the design is actually done. Have you got a better way of describing what 'rapid prototyping' means within the context of the design process?

NO / In my mind, the future of fabrication is in it becoming an integral part of the design process where there's no separation between the procedural protocols of, for example, design analysis and fabrication. This is where I always go back to nature where there is no separation between modelling, analyses and fabrication, and there is constant feedback between them. So I think it's more of a shift in design mentality than a pressure to define or give terms to a particular process within this highly integrated environment.

With regards to actual terms, I think there are two ways to consider where rapid prototyping might be going. One conceptualisation that I've attempted was to go back to craft; in my earlier work I talk about a 'rapid craft': the earlier in history, the more analogue the interaction between the designer or the artisan and his or her product in the process of making, the more intimate the relation between maker and material. There's this connection between what that specific material wants to be and the intention that is imposed on the material. So there's a lot to learn about this interaction from the world of craft, and in rapid craft I attempted to frame this as a method by which to inform our so-called 'rapid prototyping' tools with material intelligence that's more inherent to the type of product or processes that we as designers want to engage with.

SH / This is actually where I was hoping this would go when I mentioned two levels. One level is 'rapid prototyping', which is really just about getting the potential design product realised in the process earlier, so you can reflect on it; this is very much within the realm of what we traditionally think of as design. But some of the things you are proposing are a totally different paradigm from that. Before going on, I know you've done a few things recently that look at manipulating the material properties of objects.

NO / Sure, Beast was a design for a chaise longue with the aim of integrating material structure and geometry in one process, but also integrating between those various phases in the design which we've discussed; modelling, analysis and fabrication. Typically, in the Modernist chaise longue there's a separation between materials and performances, but here the idea was to work with one material system and allow that system to differentiate itself locally so that it could work both as a structural supporting system, but also provide for comfort – so you are integrating between structural performance and corporeal performance. Based on a pressure mapping, I'm distributing soft materials to support high-pressure areas, and the stiffer materials to provide for structural support of the chaise; so you're essentially combining all these materials with one system.

The methodological innovation that went along with Beast was a new type of printing that I patented and termed 'Variable Property Rapid Prototyping' (VPRP). VPRP allows you to vary material properties in correspondence with the change in the structural and environmental performance. Imagine you are printing bone tissue, and you're varying the density as a function in the changes in load; or imagine you are printing muscle tissue and you're varying its elasticity as a function of stress or flexibility. Here – in the spirit of the death of the author – the designer becomes an author of process as opposed to the author of the product where he or she is controlling the process by which those ultimately parametric physical attributes correspond to the type of performance criteria that's authoring the shape.

SH / I want to talk about this 'death of the author', but I want also to ask about complexity, because obviously you're dealing with multiple systems here that would normally be quite distinct. In a way it goes against several hundred years of post-Enlightenment reductionism in the way we normally practice engineering and design: we set these systems apart and we don't consider a structure that has structural objectives, and comfort objectives, and all sorts of other things together as one system. I was looking at one of your videos, and online and you had a phrase in which you mentioned the 'designer as gardener', which to me is someone who is not necessarily controlling these processes but is able to set them up and look at them at a higher level and to be able to select from them. So it's 'designer as gardener' as opposed to 'designer as mother nature' or 'god' who would be in complete control of those processes. Is that the metaphor you're getting at?

NO / Well it's an interesting question and I've learnt to allow for an open-mindedness with my own ideologies! But, more to the point, I think it's a question of scale. So traditionally, if you consider the architect as the ultimate form-giver or image-maker, then the architect might be known to intervene on the level of Mother Nature; this would be the analogy, where we start from the 'tabula rasa' condition, and everything is defined by the designer. But if we consider the architect not as form-giver, but as a kind of form-finder, then we allow ourselves to move into a different, more subtle, scale of observation where we become more sensitive to the type of material choices we make – Frei Otto is one such great example, I believe we're both admirers of his work. In a sense Beast was a combination of a Mother Nature approach to form, combined with the 'gardener' approach in the development of the chaise and that is because I have not yet found a way of integrating between those processes utterly. Form has to start somewhere and unlike nature, we're still not growing our products and our buildings. So yes, I think in the end it's really a question of scale, and I don't think there's a black-and-white condition where you only see yourself as a 'gardener' or as a form-maker, but it's really a sort of conversation between those scales, depending on the type of product and the type of process that you as the designer wish to author. Control is hard and soft.

SH / Well actually, that's what I was going to ask about next, because there's another concept of the gardener, which would maybe be the gardener as the breeder. Looking at evolution, it's only able to select after the fact. It doesn't really have any particular goal, which is not the way we really think of design. However the advantage of that is that evolution is of course, able to deal with far greater complexities in terms of form, because it simply doesn't have to know what all of these systems have to do in isolation from one another; it can evaluate the thing holistically.

Beast,
prototype for a chaise longue
2008–2010, acrylic composites,
Museum of Science, Boston.

This, I imagine, is an important component when you start getting to this level where you're able to manipulate very fine-scale material properties, and you're combining systems, that would normally be nice and clean and separate, into one whole. So I wonder in some way, is there a move to this more selective process rather than the instructing the system what to do?

NO / The fact that today's designers can author their own programmes to generate their own forms, almost by default, requires that the designer think of her process as one where multiple products will be the result of matching between material or performance. But in a sense, that's what we've always done as designers, so I think it's more about how these connections are made between media, than the actual appreciation or acknowledgement of these connections; I think the real question now is: 'Are we exploring all of these processes only in digital space, or do we want to intervene and have them enter physical space as well?'

SH / You mentioned there have always been editors, and this is the same sort of analogy as the gardener or the breeder. It makes me think, particularly as skills in computer coding and parametric design are lately becoming so widespread, even fashionable, that you often see a case where there's a lot of effort that's gone into the setting up of the system that generates the complexity of form, and not so much thought of the editing of the final result, if you know what I mean?

NO / Well I have two points to make about this observation; first of all, yes I agree that it's true. But where does it come from? What's the origin of this tendency? Well, I think the origin of this tendency is that we are driven by form to begin with. But if a system is set up not with form as its main intent, but rather with the interaction between some environmental criteria and, in particular, material property that you're looking to investigate, then you can really be surprised by the type of results that emerge. Again, I think there should be complete interrelation between the generative process and the editorial process, and I agree that a more performance-orientated approach to design would shift this asymmetry to give more weight to the editorial process of evaluating the performance of that particular form, matching it to its design intent.

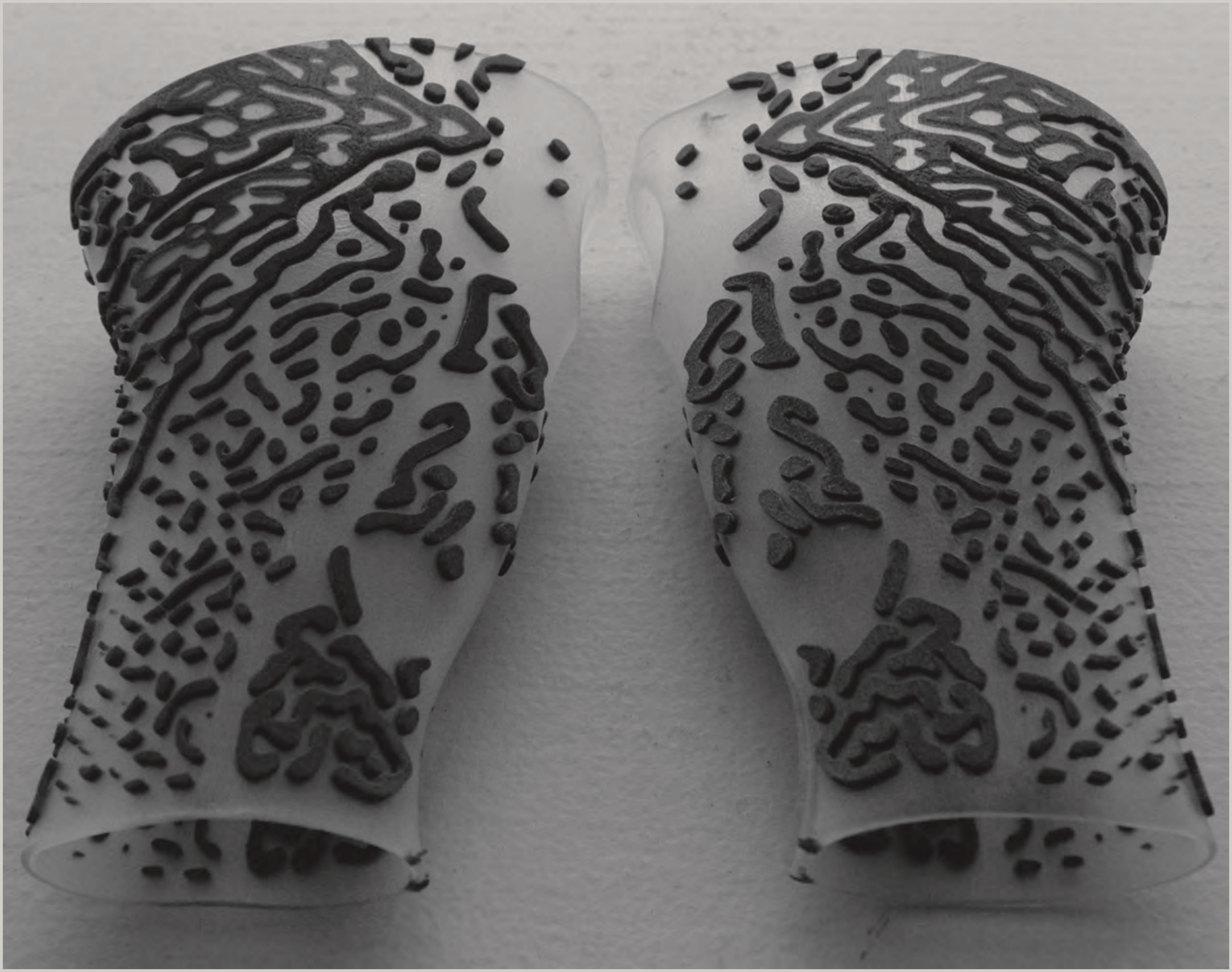
SH / One of the benefits of rapid prototyping that we talked about earlier is that you can have a model that is embodying the physical properties of the thing you're making and you can evaluate it far more holistically that you might evaluate something like a drawing or other conventional representation – you've actually got the thing there and you can test it out and that's an incredible advantage.

When we talk about performance-driven design it's quite different. Let's say you set up a series of quite explicit criteria to evaluate the performance, and sometimes they tend to override what might be considered the more holistic sorts of evaluation. We know, if we work with something like finite element analysis or CFD analysis, that these things give us a kind of feedback of phenomena that are well beyond our intuitive ability to grasp in some cases. But these are the kind of tools we use to inform our performance criteria and I worry that sometimes there is a danger that, if certain things become easily specifiable, they can dominate the decisions made about design. I met recently with some people who were working on software that can evaluate all sorts of performance criteria of a particular design. There were six or seven criteria but they didn't have anything to measure the levels of social interaction between people and how they were likely to be able to use the spaces. This would seem to me to be just as important, if not more important, as all the things that could be simulated. So, in a sense, judging by performance could actually be detrimental to design.

NO / Yes. I absolutely agree and completely share your concern. I recently visited the Sagrada Família and think about Gaudí and the idea of form-finding and a thrill for defining the parametric, and for optimising the columns to fit exactly the type of weight they need to bear, depending on their location in the church; varying the type of bricks and materials from which these columns are made; classifying them by colour – making all these conscious choices that are all speaking the language of optimisation – and yet you enter this church and it presents you with an aura that is much bigger than the sum of its parts.

Indeed, I completely agree with you that an integrated process to design should also foster ambiguity in performance and part of the problem with fabrication is that it has yet to enter the ambiguous space of design – because it's considered a service station, because it's considered as the last rank in the design process.

Regarding performance, I think that one of the problems is that it's so much identified with analysis, rather than with synthesis.



Carpal Skin,
wrist splint,
2009–2010, Acrylic Composites.
Museum of Science, Boston.

I have long been attempting to discuss the idea of a finite element synthesis approach and what this would mean to the design of objects, where every procedure is coupled with an analytic procedure, and at every point of your evaluation, you can move in any direction. That again brings a lot of ambiguity into the process of design and that requires two things; it requires that we conceive of performance as something that is negotiated; that is, we're not optimising for one performance criteria but many, including environmental as well as social performance. We have chosen to focus on environmental and structural performance because, they're easier to quantify than, say, social performance, or some aesthetic value; so it is an extremely relevant discussion to question the entire definition of performance and what it means to the designer.

The other point that I wish to make is the notion of the multi-performative. If we consider the analytic process to be driven by singular performance criteria, then we achieve some puristic result, but only within the boundaries of that singularity. But once we start considering the digital entity as one that could be conceived of as a proxy, this proxy could be loaded with multiple parameters. Then the question goes back to: 'OK, how do we now start editing this process? How do we go back to gardening this wilderness?' So, in my own work, I've tried to define a 3D voxel as a physical entity able to include various performance criteria. I completely agree with you that it is a very urgent and important topic for discussion in today's discourse.

SH / I really like the finite element synthesis idea, although I might have a completely different idea in my mind of what that means. Some of our students have done exercises where they've set up a relatively standard structural optimisation model, but instead of just letting it solve to completion, they've looked at what happens when the designer intervenes in that process. So as it's doing its optimisation, the designer could come in and say 'well I kind of like the way it's going, but let's do something a little bit different', and we can actually re-draw part of our structure. What we've found so far is that the general rule is that if the designer suggests something that is completely off the wall and doesn't make any sense, then the optimisation will just turn around and ignore it, and do exactly what it was going to do in the first place. If the designer does suggest something that does make sense, even if it might be something slightly sub-optimal, it's still within a local basin of attraction and the optimisation process goes off in that direction and does something a little bit different, guided by the designer.

Is that the sort of synthesis that you see, or is it something quite different in terms of the relationship to the designer and the finite element synthesis process?

NO / I actually see it quite differently. I think that if the designer imposes some kind of option on the optimisation protocol, that is breaking the code, then the code should be completely re-thought. I think that one of the most beautiful things about design is that state of having a beginner's mind. The code could be re-thought of constantly and in every moment in time, and with every design intention, and if that code does not serve the design intention, whatever that design intention might be, it might be a very instrumental and highly optimisation-orientated approach to the design of a truss, or it might be a highly conceptual and less defined procedure investigating shadow.

SH / The other thing that is often a problem is that, particularly in the early stages of design, standard CAD systems really just aren't very flexible, in terms of their implementation. Once you set down an arc, it's very precisely an arc and not maybe a B-spline as it might be in a sketch. In terms of the overall design process then, it seems to be much more of a dialogue between two things: the designer's mind and the computational mind. This seems to be what you're doing when you set up a system that generates form, or you set up a process to generate design, and you work with that, rather that dictating it, because it has its own objectives as well.

NO / Absolutely. The design process becomes the product, or the subject of desire. When anything and everything is possible, then of course the editorial process becomes so integral and inherent to the design process itself – inseparable from the process of the creation of form.

SH / I know you've done a Carpal Tunnel Glove as well as the Beast. One of the things I found when I was also dealing with manipulating the material properties of manufactured objects; it's always a great thing to relate them to the body, particularly because every body is different and it takes advantage of all these things that mass customisation can do. Every body has a whole lot of really complex demands on it, that making something to fit the body, and making something to accommodate the body, there's a real advantage in tuning that, and if we have the capability to do that, that's a really exciting thing.

So obviously I can see all the benefits of the sorts of technologies and techniques we've been talking about, if you're making anything that's tuned to a specific body. But when we get into the scale of architecture, we're not talking about individuals anymore, we're not talking about very specific requirements that you can map a very particular building to – a building has to accommodate large groups of people over a long period of time, possibly generations. It may change its use over a long period of time, the designer has to consider all of these things as well. I wonder about scaling up; what's your opinion? I mean, do the techniques change? Does our role as a designer change?

NO / The designer thinks in the scale at which they wish to explore a research agenda. Now, this research agenda might be constrained to a particular design space, otherwise it would not evolve as an agenda. To focus on the design of furniture and medical devices was, in a sense, an easier task, since form is already dictated by the human body and one can focus on the formation of material properties as a function of particular performance criteria in the process of fabrication.

The next thing about design is that you can always speculate, and you can always move between scales, so now the type of logic that was implemented in Carpal Skin, in the design for the Carpal Tunnel Glove, was then translated in a much larger scale in Construction in Vivo, a project I'll present at the conference. This is a project for the design of doubly-curved glass facades, skins that breathe by osmosis; the idea being that you're using small carbon nanotubes, you're making a composite between those carbon nanotubes and another composite material, and just by introducing voltage to this skin, you can change and modify the structure of those tubes; meaning that your walls can now start opening and closing their pores dynamically as they correspond to their environment. So voltage can be replaced by the movement of the sun, for instance, and then you have an entire wall system that is breathing without the need to open or close the windows; so it's a completely different notion of natural ventilation through osmosis.

SH / Finally, I just wanted to ask you a little bit about your teaching at Media Lab, particularly given your approach to design. In the traditional environment for teaching we tend to think that the style of the teacher will somehow rub off onto the students. But certainly everything you're saying (and I imagine in your teaching as well) is not about form. Do you imagine your students' work will look radically different from what you've been doing or, because you've been looking at processes, which are very much based, let's say, on natural processes, do you imagine that, having shared the same processes, you will end up with very similar formal and functional outcomes?

NO / It's a very intriguing question. I think I'd like to continue pursuing the design work that I've taken on over the past few years, independently of the group, and I would like to let the group grow independently of my own taste in ideas. Since I am intending for the group to be heavily focused on methods and techniques, I expect that the products will be quite different, but the methodologies will have in common a shared research intent that would be very similar across the various members of the group. But I think that the products will be quite different and that, of course, depends on the scale and the type of projects that we will be pursuing. I do hope they will be unique and different in expression, yet building on former foundations, and that will make it all the more exciting.

PRACTICE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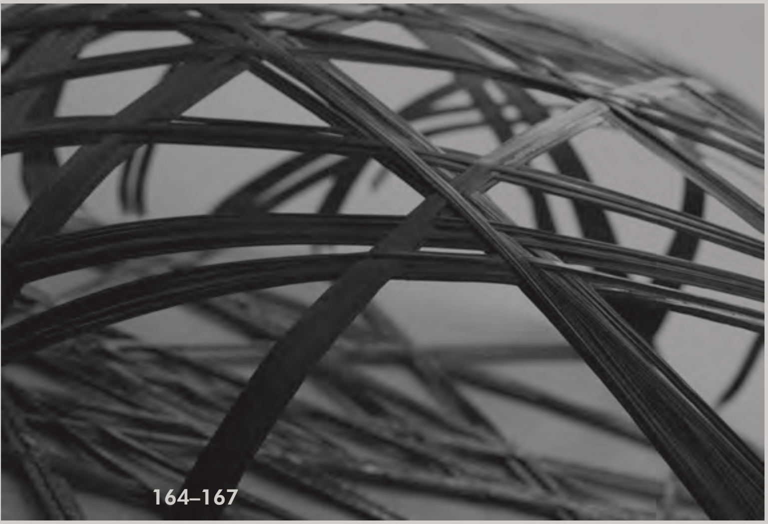
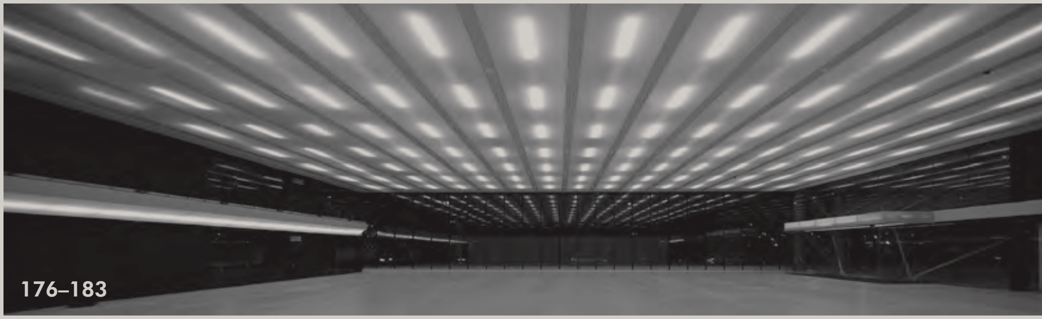
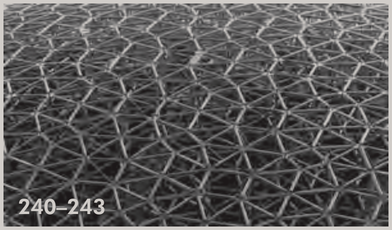
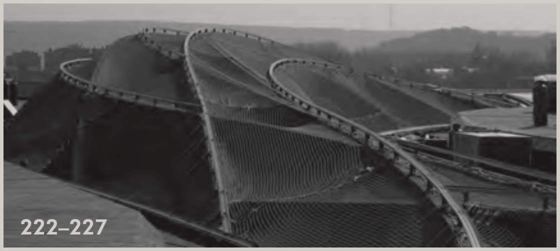
PRACTICE CONTENTS









FABRICATE celebrates that the making of the built environment has its own fascinating story, where tales of how a building or structure was made, and who it was made by, is an account of the complex endeavours that lie between representation and use. Tales on such matters as material discoveries, dexterities of fabrication, generations of prototypes, the evolution of tools and skills, the migration of knowledge and the choreography of expertise, are embedded within the substance of architectural fabric as a mummified record of how it came to be. Now, at a time when the protocols and methods of how buildings are designed and made are being substantially rewritten by integrated technologies, FABRICATE has been timed to capture a cross-section of pioneering works grappling with the challenge of using these tools both inventively and wisely. It is also motivated by the urge to document on-going strategic discussions by figures directly involved in this work as it unfolds.

For centuries, the construction of prototypes, artefacts, buildings and structures has operated on a rolling tradition of visual and verbal communication between designers, consultants, makers, clients, users and contractors. In making buildings, roles were defined by where each discipline was located on a chain from concept to execution. All were reliant on its links being successfully forged, not only to achieve results, but also to underpin their status within their respective professions and trades. Prevailing the entire process was *the design*, an assemblage of cross-referenced visualisations, specifications and quantities forming the templates and instructions to make. As it passed from one link to the next a design would change, and given the complexity of transfers involved, the resulting buildings would evolve as a *negotiated translation*. The most engaging buildings are those that have recognised this in a creative and informed way from the very outset.

Over the past decade, key relationships between design and making have been thoroughly redefined by integrated and automated digital technologies. The exchange of information between design and fabrication is no longer a slow chain of vulnerable links, but a rapid flow of data, where design and making can be a simultaneous process. A vast expansion on the remit, scope and potential of the designer has subsequently been released, allowing for their direct engagement and control of fabrication processes. Some designers, equally adept at representation as they are with putting things together, are grabbing this opportunity to redefine their role as hybrid disciplinarians. Others are remaining within the realm of making information for making buildings, but they too are adapting to the consequence of being directly connected to the processes and procedures of how their work is made. For those with a creative vision on how to further the way architecture is made, it is a fascinating time to make their mark.

Over 120 submissions from practice and industry from across the globe were received in response to FABRICATE'S call for works last autumn; a further 140 came from institutions and universities. Most were based, as we had hoped, on work in progress or ongoing construction projects, and we are immensely grateful for the richness and originality of the entire selection pool created. As an academic and practicing architect, I have a profound admiration for those who not only innovate and persist in the fraught and difficult environment of erecting ambitious and pioneering buildings, but for those who also take the time to share their expertise and experience so transparently. To sustain this vital activity and evolve a built environment worthy of future generations, exchange between institutions of education and research, and their associated industries, professions and businesses must be increasingly collaborative and in constant dialogue. The work included here is a representation of the exciting diversity of submissions we received in total, with insight on new projects from many of the world's leading consultancies and innovation firms.

Seen as a pair together in the pages ahead, both articles on the Louvre Abu Dhabi thoroughly illustrate the frontiers of building design and fabrication technologies today. The first, on how digital tools were utilised to evolve and test strategies for extreme environmental conditions, including the manipulation of interior climatic conditions, and the second, on how the same design information was deployed in the engineering and fabrication of a 1:33 scale model. On many levels it is difficult to imagine how such a vast structure could either have been designed or built in this way less than ten years ago. It is a striking example of how digital information and tooling have permeated every aspect of building design and construction, from 3D and 4D visual representation, to manufacturing capability and time-based performance analysis.

In his interview with Neri Oxman, in the previous section in this book, Sean Hanna steered the conversation towards a question on the terms 'rapid prototyping' and 'parametric'. Alternative terms such as 'craft' and 'material intelligence' were discussed as more relevant and helpful references in pushing the potential of synthesising the realms of design and fabrication. In many ways, their words resonate in each of the other interviews where the speakers noticeably avoid labelling or wrapping a uniform theoretical skin around this territory, in preference of reading evolving technologies as instigating a shift in the role, capability and expertise of the designer and what they produce. In this sense, the overarching message of the collection of articles and projects in this book is that a questioning, inventive and experimental mindset towards the making of architecture is the most essential tool at the disposal of every designer.

Finally, to illustrate a bridge between the three sections of this publication, Xavier de Kestelier shows us in 'Free-form Construction' the results of an exciting collaboration between Foster + Partners and the Innovative Manufacturing and Construction Research Centre (IMCRC) at the Loughborough University. It is a persuasive account of how changes in fabrication technology offer universities an augmented role. As cleaner, more efficient and compact technology allows advanced manufacturing to take place upon smaller footprints, university departments concerned with the design and fabric of the built environment may be positioned as laboratories to develop, test, prototype and analyse experimental constructs in partnership with business and industry. In this regard, the work presented in this book cannot be read as having wholly separate concerns, agendas or purpose. On the contrary, our intention in grouping them side by side is to reveal how much potential there is to intensify creative exchange.

VILLA NURBS

ENRIC RUIZ-GELI & HIS TEAM AT CLOUD 9, FREDERIC AMAT & TONI CUMELLA

'Villa Nurbs' is a family house located in Empuriabrava on the coast of Girona, Catalonia. Originally built on a swamp, it is now one of the country's primary regions for tourism, containing one of the world's largest marinas. The Villa features vivid, wave-like shapes that use ceramic panels as protection against solar radiation. The ceramics for the north wall of this building were produced using digitally cut moulds under the direction of Toni Cumella. These pieces form the building's ceramic 'skin' and are shaped in a manner inspired by the scales of a reptile, and were painted by Frederic Amat. Villa Nurbs integrates such traditional materials with latest-generation materials such as Corian panels by DuPont and ETFE segments by Covertex. This is an account of the project's key concepts and stages of fabrication.

KEY CONCEPTS AND AIMS

1. An early experiment involving breaking ice informed key spatial organisations.

2. Natural materials would be used.

3. The Villa would be defined as a 'landscape of pavilions' and 'a platform for living'.

4. The landscape would be constructed as a '3D topography' using NURBS (Non-Uniform Rotational b-Spline).

5. Fabrication of Villa Nurbs would optimise constructive resources using CAD/CAM construction processes.

6. The 'platform' would be created in a scalar progression from climate, to geography, landscape, then skin (NURBS).

7. Invited industrial designers would work on the skin of the NURBS, looking for a cellular and chemical approximation to materiality.

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1: Night view of north facade with the corian skin overlooking the Empuriabrava cityscape.

2–3: Top view of the ETFE roof (2) and the ceramic skin. The unique ceramic elements require a unique mould (3).

4: Entrance made out of fibreglass, translucent concrete and ceramic skin.

8. Villa Nurbs would seek to define different atmospheres inside the skin, reflecting content, or its capacity to absorb the hardware of the house.

9. The skin would be reactive and manage energy and privacy. It is not an abstract design but the superimposition of different diagrams.

CERAMIC SKIN

The ceramic skin opens a new perspective in the field of architecture for the definition of facades. It is made up of a series of ceramic units designed in a way that, seen as a group, will work as a wall of vegetation would. Depending on the direction the units face, this skin has the capacity to protect the building from the sun, the rain, or strong winds, and to allow the sea breeze to permeate the structure. A network of tensed cables fixed to the metal structure of the building hold these ceramic pieces up. Together, they form the outer layer of the facade. Amat paints each one of the ceramic pieces with enamel. The geometry of these pieces is developed on a 3D virtual model using Rhino and Microstation, which is later produced by means of digital-plot files, following a digital fabrication process. These processes link computer-aided design software and CAM machine software which are used for the milling of wood pieces. The dialogue between design software and manufacturing software makes the physical production of the virtual model possible: ceramics versus the digital era.

The skin-like facade system is made up of deformed pieces of Corian that are 6-mm-thick, fixed to a network of tensed steel cables, which measures 500 x 900 mm in total that are attached to the structure of the facade.The specific shape of each of these pieces is acquired through a heating process, which gives them a characteristic elasticity, and enables their later placement on a mould. Given that the materials which make up this facade are translucent (and transparent), the facade itself is also a translucent element. The inner space can be flooded with daylight and the outside can be illuminated from within at night. As long as there is a source of light, this is a facade that illuminates both inwardly and outwardly.

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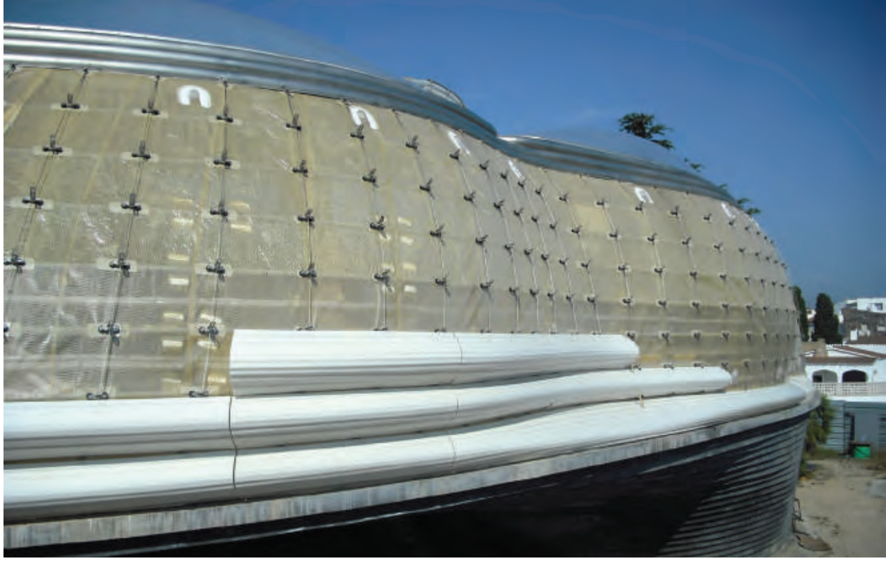

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5–6: The fabrication of the corian as well as the ceramic skin required unique moulds for every panel. Once the mould has been CNC milled and laid out, the Corian panels were trimmed at the edges.

7: View of the cantilevered side of the villa with ceramic and window elements.

ETFE COVERING

This is a new light-roofing system made up of four layers of ETFE. Three of the layers are transparent (top and middle layers) and one is translucent (the inner layer). A supplementary sheet of 98 per cent opaqueness with a circular pattern is divided between the two middle layers, to which it adheres. These layers define three inflatable elements, or cushions, that work with differential air pressures. This is an almost immaterial covering. The sum of its five component layers make up a thickness of only 1.25 mm and 99 per cent of its volume is air. The thickness of each ETFE foil is 200µ, containing air at a pressure of 300 pascals inside every cushion. The pneumatic daylight control system is regulated by the air pressure in the inflatable upper and inner cavities, which allows the layer of ETFE that separates these two cushions to go up or down, and the two parts of the opaque sheet set among the inner layers to come into contact with each other. That fact that there are several cushions, and thus several air spaces, also makes it a good thermal and acoustic insulation system.

SUMMARY

In *The Mathematics of Architecture* (2010), Jane and Mark Burry describe Villa Nurbs as ‘uncompromising’ and they continue: ‘It is as if a CAD project has been directly translated from computer-generated Non-Uniform Rational B-spline surfaces (NURBS) directly to built object.’ We would agree with this assessment, and add that Villa Nurbs has been a key project in defining the aspirations of the office to continually exploit digital technology and material capability to achieve a comprehensive architecture for our times.

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C-STONE & C-BENCH

PETER DONDERS

The C-Stone and C-Bench by Belgian designer, Peter Donders, are machine-made from a single string of carbon fibre that has been guided around a temporary mandrel. The result is an airy but strong structure, described by Rob Cassy *(The Garden Design Journal)* as 'calligraphy in 3D'. The work has been developed in collaboration with composite technology facilitators Seifert and Skinner & Associates (SSA), who specialise in developing equipment and software for bespoke automated processes.

Using advanced industrial materials from, amongst others, the aerospace sector, SSA have fabricated a variety of artefacts in carbon fibre and epoxy resin, using a process called filament winding where a band of fibres, impregnated with resin, is wound around a mould or mandrel in a specific pattern to produce the desired part's geometry. The resin is heat-cured and the part solidifies. The mandrel is then removed from the finished part, revealing the skeletal woven structure. The process is typically used in the manufacture of pressure vessels and pipes for industrial use, where fibres are wound in a regular and dense geometric pattern.

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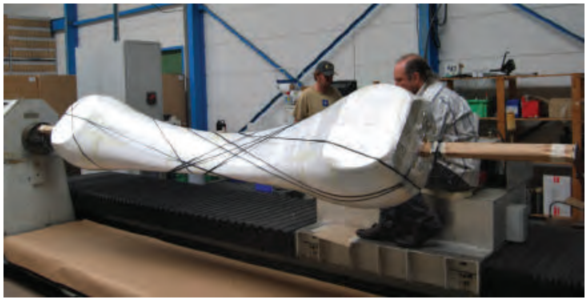

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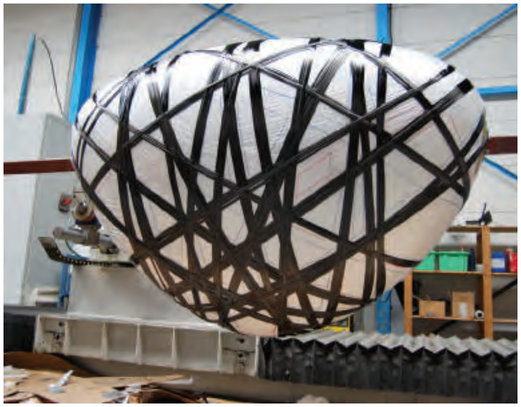

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The idea for C-Stone and C-Bench was to challenge this convention by exploring the effectiveness of more random-looking geometries on an organic shape. As it turned out, this was quite a challenge to fabricate.

MODELLING

Overall shapes for C-Bench and C-Stone were developed in the Non-Uniform Rational B-Spline (NURBS) based program Rhino in April 2010. The software also allowed for the generation of CAD/CAM data to drive a five-axis CNC mill in manufacturing the tool (mandrel) that the fibres were ultimately wound on. Rhino's T-Spline plug-in was also used to add detail, create non-rectangular topology and edit complex free-form models whilst maintaining NURBS compatibility.

GEODESIC PATHS

To achieve the concept of forming the structures from a single uninterrupted wound filament over an organically flowing surface, an exact description of one continuous geodesic path over the complex surface of the base-shape was required. This was generated by manipulating a chain of smoothly linked multiple geodesic paths until they all described a single route, using the geodesics function to define a start point, end point and base surface in Rhino's Grasshopper plug-in. After extensive experimentation and changes in the used algorithms, a method was found that generated the continuous path on the surface. Using variations in the parameters of the algorithms and semi-automatic selection of the individual circuits, the desired look could finally be achieved.

The final design stage challenge was to get the path data out of Grasshopper in a form that could be utilised by the computer-controlled filament winding machine. This was achieved by exporting the path data in a CSV (Comma-Separated Values) format into the CNC software for the filament-winding machine.

PROTOTYPES.

In late August 2010 the first prototypes were made. Structural testing on a scale-model form of the C-Bench returned successful results, and as soon as the big moulds were ready, final full-scale versions were identically fabricated. Using this process, it is proposed to manipulate the filament path to a different configuration for each iteration. As required for construction purposes, it can be decided during the design process where to put more – or less – material and control the locations as well as the number of

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fibre crossings, both of which will determine the maximum carry load of the object. SSA's filament winding facilities can accommodate objects up to 1,500 x 9,000 mm.

SPECIFICATIONS

C-Bench
Weight: 5.7 kg
Fibre: 320 metres
Size: 3,000 x 600 x 400 mm

C-Stone
Weight: 6 kg
Fibre: 462 metres
Size: 1,640 x 1,150 x 400 mm

The fibre band consisted of six 24K tows, 24K refers to the number of individual filaments in the carbon yarn.

1: C-Stone detail.

2–6: Manufacturing process for C-Bench (2, 3, 4) and C-Stone (5, 6).

7: C-Bench: the final product.

7

GALAXY SOHO LARGE-SCALE CLADDING CONSTRUCTION IN CHINA

CRISTIANO CECCATO,
ZAHA HADID ARCHITECTS

The Galaxy SOHO Project is a new commercial mixed-use development designed by Zaha Hadid Architects (ZHA) for SOHO China, Beijing. The project has an area of over 360,000 square metres and is currently under construction in Beijing. Here we focus on the design, geometric development, engineering, fabrication and construction of the project's cladding system, in particular. The desire is to relay the steps necessary to implement such a design within a particular context, in this case, a private-client project in the People's Republic of China. The project can be considered a 'Work in Progress' as construction is in full progress at the time of writing.

Zaha Hadid's interest in form and its geometric definition goes back more than 30 years; a central preoccupation of ZHA, has therefore, been the exploration of complex geometry, its representation and increasingly, over the past ten years, its translation into physical form through built projects. The Galaxy SOHO can be considered representative of the digital design, BIM coordination, documentation and fabrication techniques currently being developed and employed by ZHA.

PARAMETRIC DESIGN PROCESS

During the early concept phase, the project was originally designed using 'subdivision surface' technology within Maya to produce the underlying master surface 'parametric driver' geometry that would define the design intention for the project – in this case, a set of four egg-shaped volumes that are fluidly interconnected to create a single building mass. This 'driver' geometry forms the basis for a 3D digital coordination process using CATIA/Digital Project and defines all downstream project geometry, such as slab profiles, facade contours and cladding surfaces.

BIM COORDINATION

A project of the size and complexity of Galaxy cannot be accurately designed and coordinated using 2D drawings alone. Construction documentation is therefore coordinated through the use of a detailed CATIA/Digital Project BIM model; the 3D model is used in all the conventional BIM processes, including geometry development, digital coordination, clash-detection and drawing production. In the case of the facade system, the 3D model is also used as an

instrument of contract, effectively according geometric authority to the digital data files at the tender stage.

'STAGE 0'
FACADE GEOMETRY: DOUBLE-CURVED STRIPS

The facade of the Galaxy SOHO project is generated by slicing the 'driver' surface horizontally at each floor, producing horizontal bands of inset glazing divided by strips or 'fascias' of surface geometry that provide a reference to the original underlying shape. Each strip is, at this stage, a simple horizontal trim at each floor of the original double-curved surface, and as such it is double-curved and unrationalised.

MOCK-UP PROCESS FOR MATERIAL SYSTEM EXPLORATION

As part of the design development process, ZHA and the client elected to build a series of facade mock-ups in different materials to assess geometric complexity, contractor capability in China as well as material performance, constructability and aesthetics. An area of the project was chosen that allowed the team to test the broadest possible set of geometric conditions. A tender package for the mock-up was issued to fabricators as a combined 3D model and 2D drawing documentation set. The same identical area of facade geometry was executed in sheet metal, steel plate, fibre-reinforced plastic (FRP) and glass-reinforced concrete (GRC) panels respectively. This was combined with a formal facade contractor pre-qualification process to officially evaluate which candidate facade contractors would be capable of delivering the facade at an acceptable quality should it be selected during tender.

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'STAGE 1'
RATIONALISATION – DEVELOPABLE SURFACES

The mock-up process led to the choice of material for facade, in this case, aluminium sheet metal panels. The geometry of sheet metal ensures that the manufacturing process minimises the use of expensive forming techniques such as moulds or pressing, thus keeping the costs down and expediting execution. Using such single-curved surfaces to rebuild the 'Stage 0' double-curved geometry strips (the 'driver' surfaces) implies of course, approximation or rationalisation of the original shape ('Stage 1' Rationalisation). However, at the scale of the panels and fascia width, the visual difference per fascia band is negligible, and with the exception of highly-curved areas, allows about 95 per cent of the building facade to be implemented in single-curved sheet metal geometry, with considerable savings to the project. However, this first stage rationalisation still implies that each facade panel is geometrically unique.

'STAGE 2'
RATIONALISATION – CONE STRIPS AND DEVELOPABLE SURFACES

A second step in simplifying the geometry is to substitute as many of the developable surfaces as possible with cone segments. Within each conical strip, each constituent fascia panel is identical. A parametric definition of each is constituted of cone canting angle, radius, height and panel-arc length. These 'cone strips' are assembled so that each sequence of conical panels tangentially connects to the next cone strip, ensuring a visually smooth geometric continuity along the facade. Across one floor, all cone segments are made from sections of a common underlying cone (i.e. common canting angle). To achieve this, each 'Stage 1' fascia strip is assessed for its drafting angle (i.e. vertical inclination of the fascia). A visually acceptable range of draft angle was established, the mean of which was taken as the common 'canting' angle of the cone for each specific fascia strip. The strips were implemented as 'parametric cone strips' which ensured tangency at each end and a commonly adjustable canting

1: Galaxy SOHO as it will appear when completed in late 2012, overlooking the south-east.

2: Galaxy SOHO frontal fascia panel model. The lower part of the image shows colour coding to describe different types of panels: fuchsia are double-curved; blue are single-curved developable; white are fully flat. Brown, yellow and green tones depict families of rationalised, identical, conical panels. This model was used as an instrument of contract for the tender award and subsequent fabrication of the cladding panels.

3: BIM Coordination Model showing cladding, structure, interiors and MEP systems. October 2010.

angle across the strip. Where the 'Stage 1' developable strip's draft angle would exceed the acceptable range of draft, the cones were omitted in favour of maintain 'buffer strips' of generic developable surfaces, in order to maintain a uniform appearance of the overall building. Approximately 90 per cent of the fascia strip surface was able to be rationalised using cone strips.

'STAGE 3' RATIONALISATION – COMMON FAMILIES OF CONES

A further step in rationalisation is to further manipulate the parametric cone strips to find common parameters across the four different towers that allow a cone strip present in one particular tower and floor to be re-used in another tower on a different floor, with greater or lesser numbers of constituent cone panels.

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4: 3-mm aluminium material-test mock-up produced by Permasteelisa, October 2009. Several geometric conditions are explored as well as rationalisation testing. This mock-up was one of several material validation built to facilitate a material systems decision for executing the project.

5: Galaxy SOHO on-site factory f or concrete reinforcement bar. Manual labour is still the key method of construction.

6: Tender mock-up by Yuanda, November 2010. Each tendering facade contractor was required to produce a full-scale mock-up of the facade system as part of their bid. This mock-up shows the continuous-pipe support details for double-curved portions of the building, as well as variable-geometry fine-tuning control jigs for final panel alignment within specified tolerances.

This is done by recording local parametric conditions at each cone strip insertion and looking for very similar parametric conditions elsewhere in the project. Parameters are matched on both sides to assess for visual similarity to the 'Stage 1' strip, and if acceptable, a parametric cone strip can be re-used in another part of the project. This reduced the number of cone strip families by about 30 per cent A total of over 52,000 different facade components, of which over 18,000 were glazing units and 34,000 facade panel units, are identified in over 800 families of components using the 'Stage 3' Rationalisation process.

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'STAGE 4'
OPTIMISATION – MATERIAL BEHAVIOUR-BASED REDUCTION OF FAMILIES

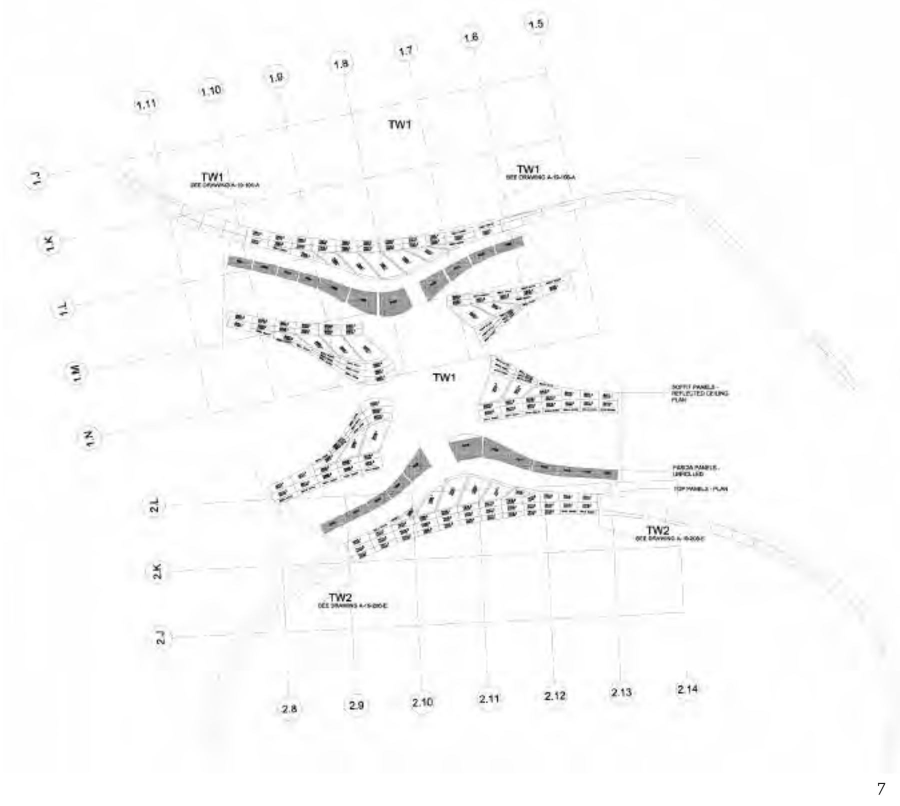
A further level optimisation can be achieved by examining which cone families can be grouped together as one common family, based on the similarity and proximity of geometric values of individually-calculated cone types. This is a geometrically imprecise process which is based on (a) manufacturing and construction tolerances and (b) the facade contractor's understanding of material behaviour. For example, cones that have a common canting angle and very similar radii (for example, 59 and 60 metres) may have an arc depth variation of only a few millimetres. These may be grouped together into a single family, as the material flex required is within construction tolerance as well as material elasticity, allowing a reduction of panel families by a considerable factor. This will be achieved post-tender.

TENDER STAGE LAYOUT

In order to facilitate an understanding of the facade panel geometry, the team produced a formal 2D layout (setting-out) of the 3D panel geometry, including a correct geometric unfolding of single-curved (developable and conical panels), a projection of sill and soffit panels and the recording of each conical radius, start and end point coordinate data in order to facilitate production and better understand the 3D digital database of the facade. This 2D information set forms an integral part of the 497-page A0-size facade tender package of the project submitted in September 2010.

3D CONTRACT DOCUMENTS & TENDER PROCESS

The facade system of the Galaxy SOHO project consists of a complex combination of flat and single- and double-curved panels that cannot be described accurately through conventional 2D documentation. As a result, the facade geometry components of the 3D BIM model were developed by ZHA to a high degree of precision and coordination and, together with conventional drawings and details, were issued as instruments of contract for the tender and subsequent construction of the facade. The tender process itself was subdivided into two main components: each tendering contractor submitted traditional tender-return technical documentation consisting of system development, execution details and the contractor's means and methods. Additionally, each contractor was required to build a 1:1 mock-up that demonstrated achievable surface panel execution quality and continuity as well as system constructability through detailed sub-frame engineering. Together with the contractor prequalification this process resulted in a formal appraisal and scoring of each contractor by both ZHA and SOHO; the contract award is expected by December 2010.



'STAGE 5'
POST-TENDER VALUE-ENGINEERING

Following the successful award of the facade contracts, it is conceivable (though by no means certain) that further cost reductions will be mandated by the client to reconcile the tender returns with allowable budget, while also reducing risk. This is commonly termed 'value engineering' and is typically driven by contractors. In this case, ZHA is pre-emptively developing further rationalisation solutions to explore further reductions in form complexity and component geometry, while also retaining overall aesthetic quality and geometric coherence in the design. Visual tests will be made on the 3D model to determine which elements of the design – based on curvature, reflection and visual continuity – can be selectively geometrically simplified while also responding to fabricator requirements.

POSTSCRIPTUM
CURRENT PROJECT STATUS – NOVEMBER 2010

As of November 2010, the first part of the project, the showroom element in the northwest corner of the site, has been completed using the same 3-mm aluminium sheet-metal facade detailing method and coordination framework. This single-storey building is now being used by the client as a sales and negotiation office to sell the office and retail spaces in the main building. At the same time, it served as a construction laboratory for further development and refinement for the main building facade tender. Concurrently, the main building site is advancing rapidly. Foundations are complete and the structural frame using steel reinforced columns (SRC) is being installed on the upper levels of the towers, with the shapes of the egg-shaped buildings becoming clearly identifiable. The project is expected to be at grade level by the end of 2010, with the superstructure being complete in 2011. The first cladding panels are expected to go on in late Spring 2011, so there will hopefully be some interesting results in time for the FABRICATE 2011 conference.

7: Geometric set-out drawing illustrating the geometric conditions for panel assembly. The greyed-out areas show the limitations of 2D description of double-curved components.

8: Site progress, October 2010. Completed Showroom on the bottom right. Eight cranes simultaneously assemble the four towers.

8

MEDIA-ICT

ENRIC RUIZ GELI
& HIS TEAM AT CLOUD 9

MEDIA-ICT is located in the 22@Barcelona district, a new science and technology quarter that occupies 200 hectares in Barcelona's former industrial heartland of Poblenou. As Barcelona's main economic motor for over 100 years, Poblenou has been regenerated into a new urban zone to promote collaboration and synergies between the university, technology and business. 22@ Barcelona district has been identified as a new centre of European excellence in new technologies, such as audio-visual, ICT, biosciences and energy sectors. The district will create up to 3,200,000 square metres of new, flexible and unique technological spaces for innovative companies, as well as 400,000 square metres of new land for installations, 4,000 government-protected flats and 75,000 square metres of green areas that will ensure the urban and environmental quality of the new economic centre of Barcelona.

MEDIA-ICT is a communications and interaction hub for businesses and institutions specialising in the world of information and communication technologies (ICTs), as well as for the media and audio-visual sectors. The project was designed by architects CLOUD 9, and structural engineers BOMA S.L., AGUSTÍ OBIOL. The programme for the building consists of:

1. Information and Communications Technology Centre (ICT): a 'hub' facility available to both the general public and businesses developed in conjunction with the Barcelona Digital Foundation.

2. The MEDIA-ICT (Incubator): a facility that offers infrastructure, development and financial support for entrepreneurs in the media sector.

3. The MEDIA-ICT (Landing and Accel Programme): a facility that offers development space and services for international business initiatives that wish to establish a base in Barcelona and to participate in the system of Catalan innovation.

4. ICT Technological Centre: a training facility that offers mechanisms for the incorporation, use and application of ICTs so that businesses and institutions can increase their productivity and competitiveness within the digital economy.

1: Featuring a reactive ETFE skin, this 'intelligent' building regulates energy through daylight and occupancy sensing.

2: Elevation view of the transparent building skin.

3–4: Development of network lattice.

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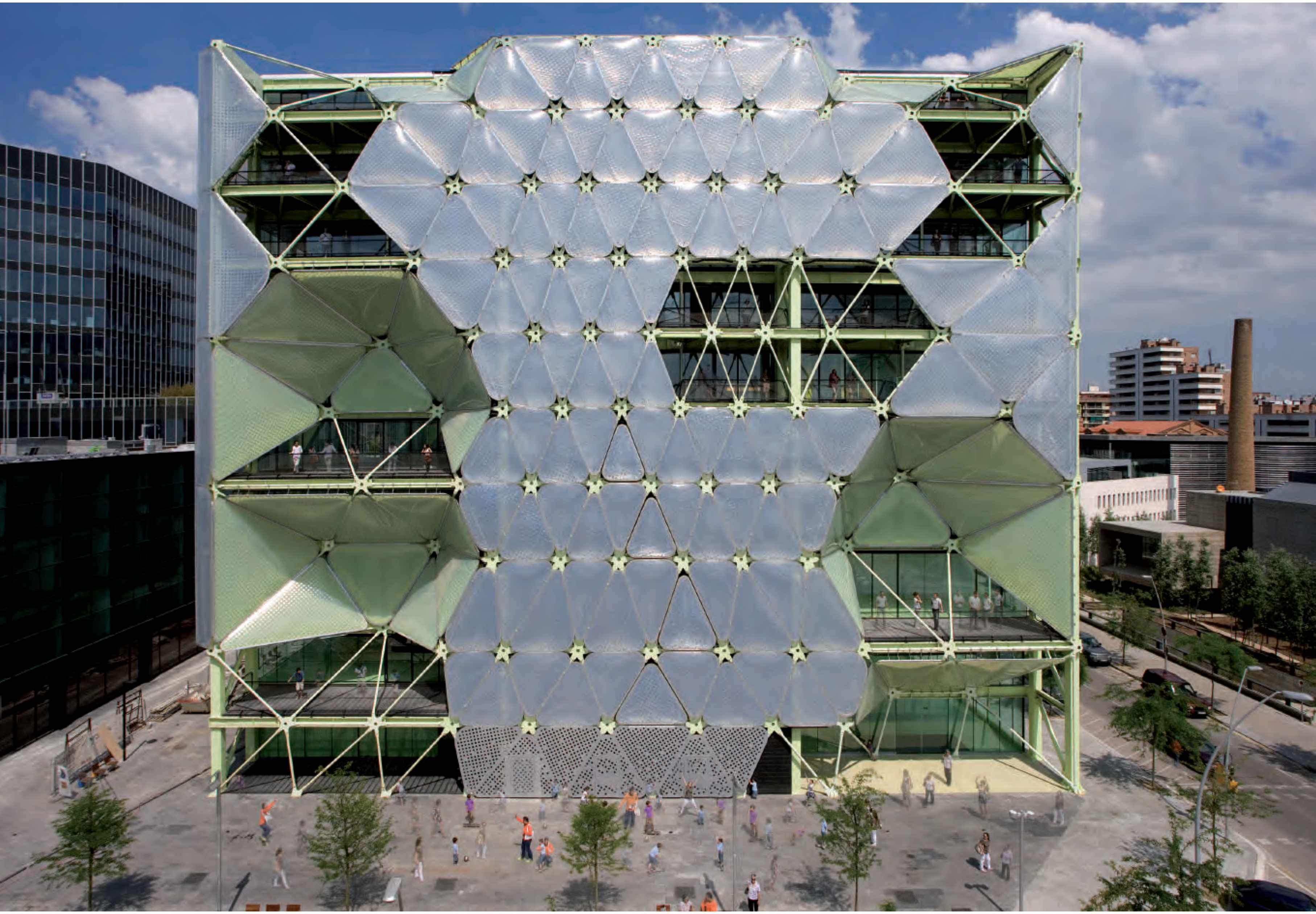

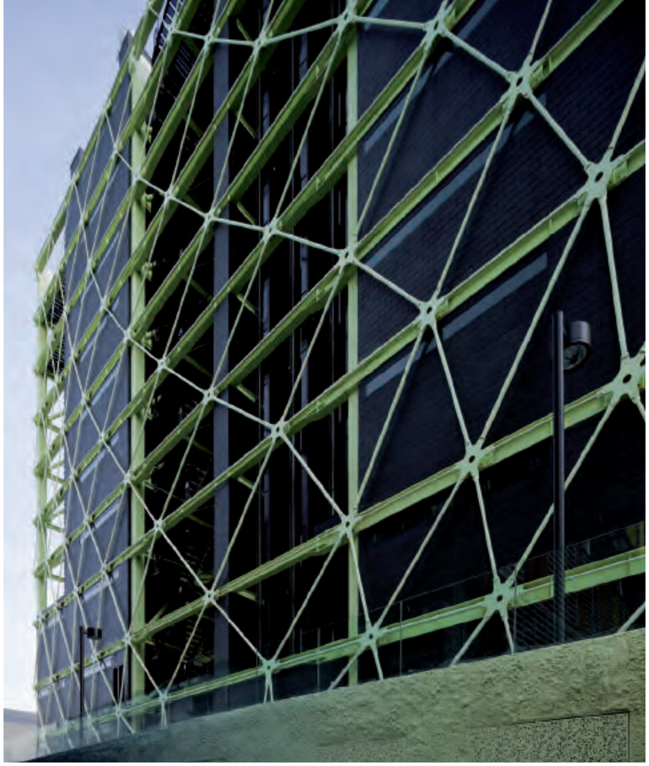

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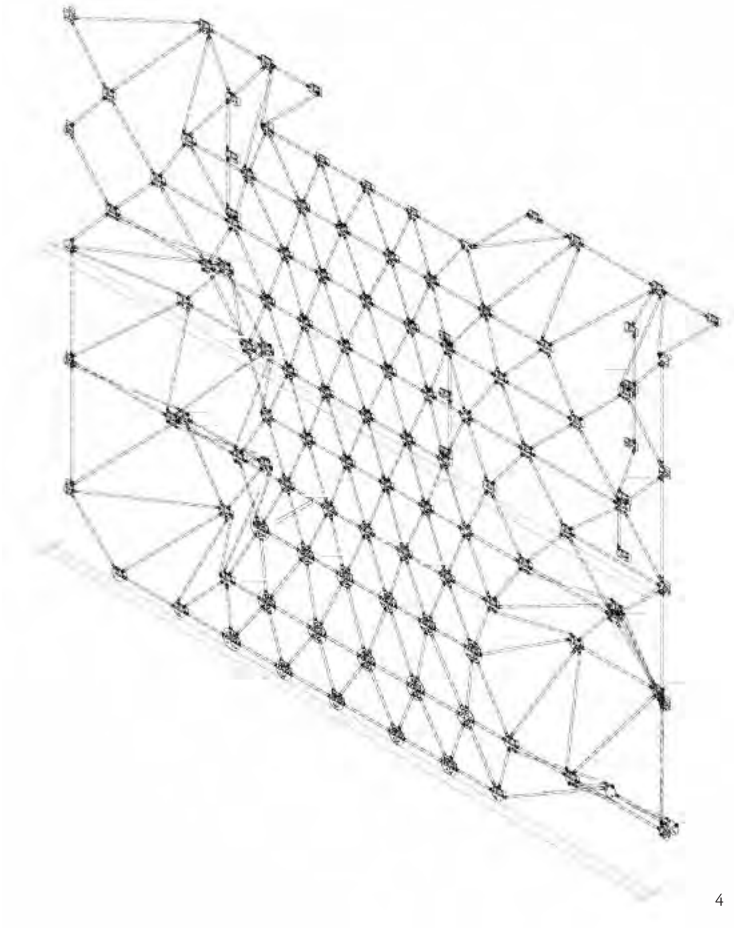

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We are experiencing a digital revolution. Between 1850 and 1950, factories whose technological and structural advances created work spaces, such as Saulnier's Menier Chocolate Factory at Noisel-sur-Marne, (1871–1872), Esders Sewing Machines Factory in Paris (1919) and Berhens AEG Turbines Factory Berlin (1908), were the cathedrals of architecture. Now, in the information era, architecture has to be a technological platform, in which bits, connectivity, new materials and nanotechnology are more important than old materials. We are living in an electronic, immaterial world, in which what is important is the network's design, not its physical size.

MEDIA-ICT is digital architecture, constructed using CAD/CAM digital processes. Its facade does not represent industrial, series construction: instead it evolves and represents digital construction, the construction of information. It consists of a primary steel structure, composed of four rigid, braced frames, 14.25 metres apart. The frame type consists of steel 'Fink' beams made of seven- and eight-section forged-metal girders. Each frame has a support beam that transfers their load to 'galleries', the rigid support centres. Each of these elements defines a space with a different structural density:

· Zero density: a clear-span ground floor space of 36 x 44 metres.

· Low density: maximum flexibility office floors with minimal interruption, provided by traction optimising structure, making it possible to divide different uses and different users

· High density: galleries. Large structural beams define smaller and more inflexible spaces that correspond to centres of communication, installation supports, bathrooms, roof terraces and courtyards.

Using 2,500 square metres of ethylene tetra fluoro ethylene (ETFE) cladding, MEDIA-ICT will enable energy savings of 20 per cent and will score 42 points of the maximum 57 points envisaged by the decree on environmental criteria and energy eco-efficiency for buildings.

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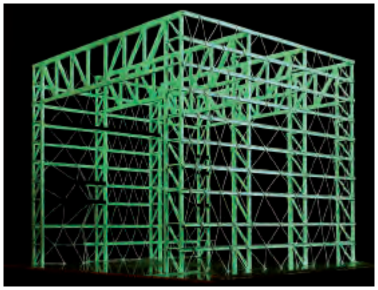

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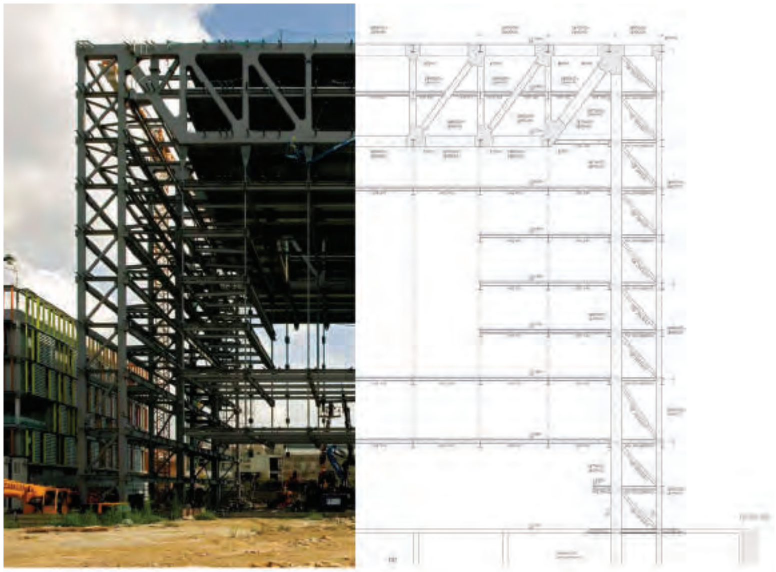

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5–6: Scale models.

7: Digital fabrication of steel elements.

8: Main metal structural frame consisting of four large porticoes, from which the floor structures hang, leaving the entry/ground level free of any structural features.

9: The cushions on the east-facing Sancho de Àvila facade incorporate a pneumatic light-control system. The positive/negative printed design on the membranes produce an opaque surface when overlapped.

The advantages of ETFE, in this instance, provided a solar filter and facade with a thickness of 200 µm, an ultraviolet coefficient of 85 per cent and density of 350 g/square metre. It is also auto-combustible and its elasticity could be exploited for geometric form-finding. Furthermore, it is anti-adherent, which prevents it from becoming dirty and requiring cleaning maintenance. At the same time, it does not lose its characteristics of elasticity, transparency or strength over time. The ETFE cladding on MEDIA-ICT is inflatable, with up to three air chambers. This not only improves thermal insulation, but also makes it possible to create shade by means of the pneumatic system. The first layer is transparent, the second (middle) and third layers have a reverse pattern design that, when inflated and joined together, create shade or, in other words, a single opaque layer. When the second and third layers are joined, creating shade, the inflatable section only has one air chamber.

In this way, it is possible to manage an entire facade simply by the movement of air. This is not done with industrial mechanisms, but with air management, which has very favourable and energy-economic results. According to the solar study, the north-east facade (known as the Roc Boronat Facade) receives around three hours of sun per day during the morning, and it does not require a system of external solar protection. Instead, we are applying internal protection based on screen-type blinds. The Sancho de Àvila facade (south-east) receives an average of six hours of sunshine a day, requiring an external solar system based on a double layer of cladding that is regulated, domotic structurally light, with low energy consumption and great illumination efficiency.

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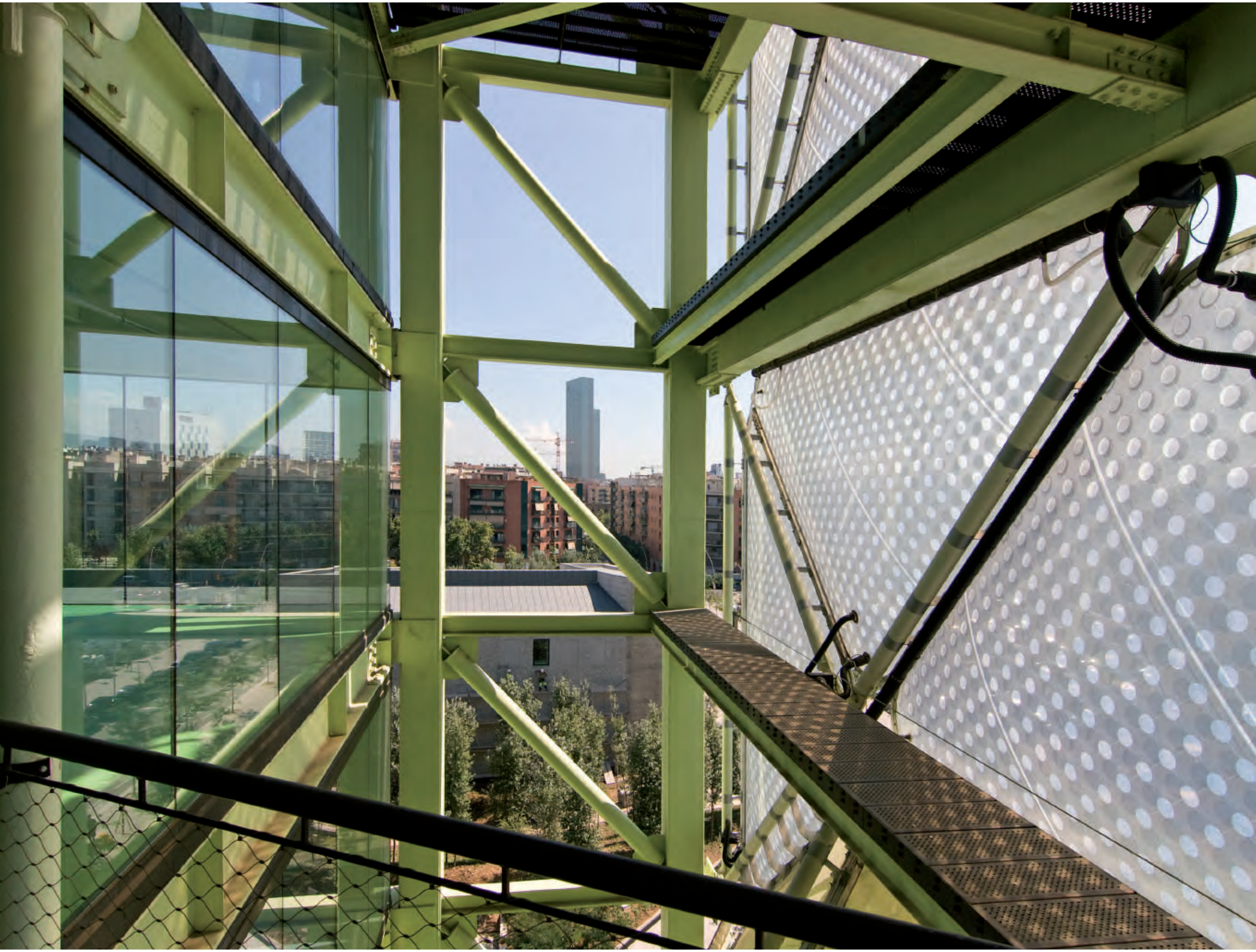

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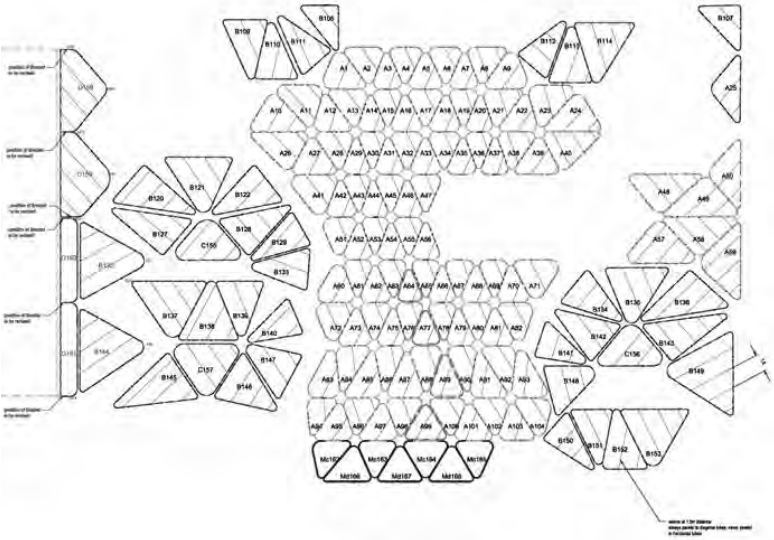

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The solution is an exterior 'film' of material with a variable ETFE solar filter in Diaphragm configuration, constructed with three layers of ETFE, with constant pressure and variable circulation of air between the chambers. The CAC Facade (south-west) also receives an average of six hours of sunshine a day. For this reason, thanks to the powerful heat energy that enters, the suggested solution is the so-called lenticular solution, based on two layers of ETFE, filled with nitrogen. In this case, we use the air density of its particles in order to create a solar filter. This is a mechanism created following exhaustive research, that represents a very low economic cost with respect to the project, accounting for 5 per cent of the total. We are in an area of ICT innovation, where energy management is the most important objective. For this reason, the theme of the MEDIA-ICT building is how architecture creates a new balance with the digital use of energy.

Augmenting the air density of the ETFE cushions with nitrogen particles, the G-factor of the building goes from 0.35 to 0.19. The system activates itself automatically with a temperature sensor network. At this point, it performs and regulates the solar energy with a filter in the facade, which combines a nitrogen particle system with air from the ETFEs and creates a cloud that protects the building's interior.

10: With their triangular shape, the cushions on the Sancho de Àvila facade reflect off and expose the structure underneath.

11: Layout of all the cushions on the Sancho de Àvila facade.

12: Within the @22 district in Barcelona the Media-ICT building hosts a hybrid programme ranging from an incubator for young companies to spaces for large corporations.

13: The brace in the light well illustrates the various structural densities at work – a transition from the large beams to low-density tension elements.

13

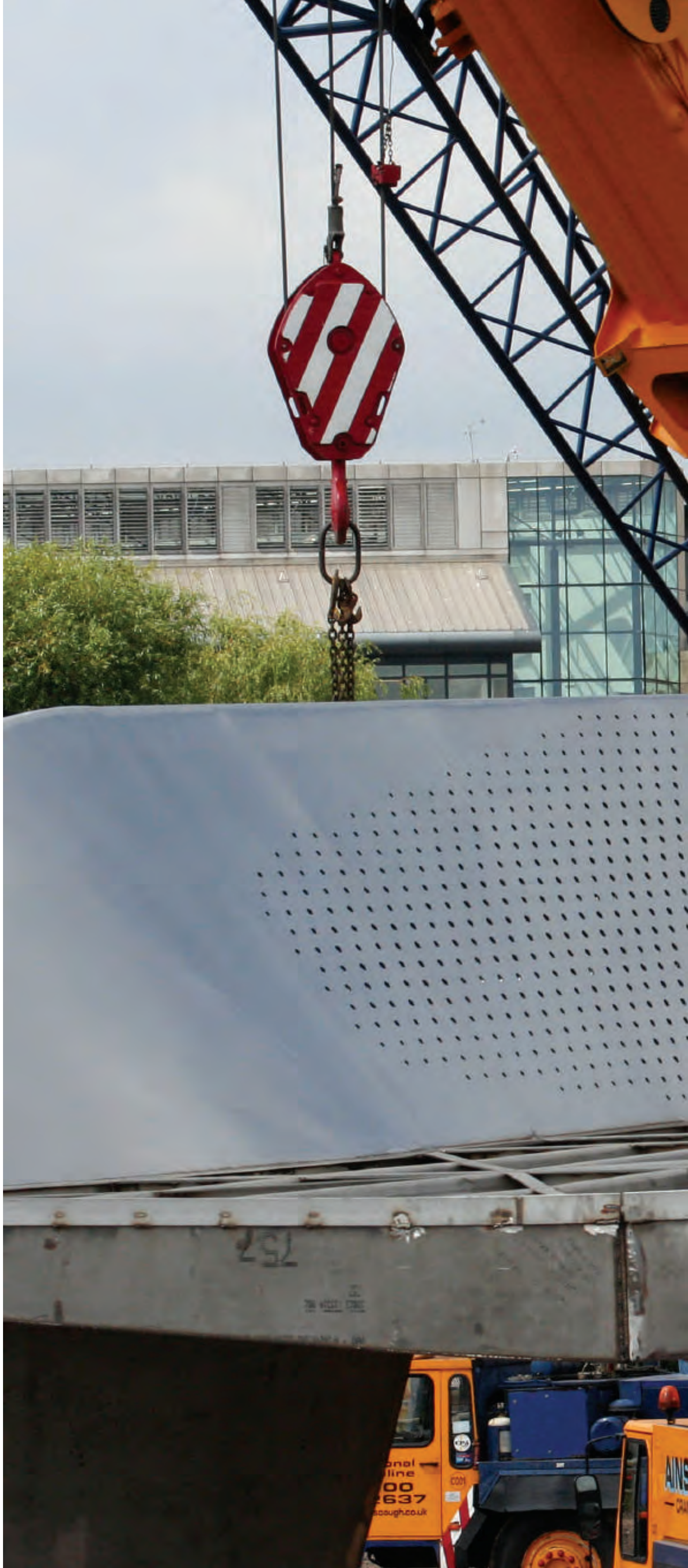
MEADS REACH BRIDGE

TIM LUCAS,
PRICE AND MYERS

There is an old drinking game where a tissue is wrapped over the top of a glass and a coin is placed in the middle of it. Players take turns to burn a single hole in the tissue with a lit cigarette. The player who causes the coin to drop through the tissue buys the next round. Without realising it, the players are exploring a key aspect of the design of Meads Reach Bridge in Bristol; how to take as much material as possible away from a structural 'stressed-skin' surface without causing failure.

The bridge is the result of a design competition for a foot and cycle bridge organised by Bristol City Council and property developer, Castlemore. The structure links the two sides of Castlemore's Temple Quay development near Temple Meads Station, which are divided by the Floating Harbour. Teams were to be made up of architects, an artist and engineers.

The Floating Harbour runs through the middle of Bristol and is the original route of the tidal River Avon. In the nineteenth century the tidal river was diverted and lock gates were installed at either side of the city centre to create a stretch of water with a constant level.




AINSCOUGH

The water is bound by quay walls, which in the past allowed ships to dock alongside the glass works that formerly occupied the site.

The site for the new Meads Reach Bridge is located between two other bridges. A nineteenth-century brick arch bridge by Brunel lies to the east and carries the railway into Temple Meads Station. To the west there is a fairly flamboyant footbridge constructed in the late 1990s and, in many ways, it is typical of that era.

INITIAL DESIGN PROCESS

After visiting the site, the architect, artist and engineers sat down and deliberately decided not to draw anything. Rather, they wrote down qualities that they would like the bridge to have. The list they wrote is as follows:

· It should be light against the dark brick of Brunel's bridge.

· It should be one thing, not many.

· Its deck, balustrade, lighting, structure and handrail should be one thing.

· We should design its reflection.

· It should be possible to draw it in no more than three lines.

· At night it should not be lit, it should be the light.

· It should explore a singular structural principle.

· It should land easily at each end.

· It should draw the traveller's attention to the water itself.

· It should be a lovely object since it will stand for many years in a construction site.

· It should be made from one material, which uses local expertise.

· It must be something that none of the collaborating parties could design without the others.

Only after these points had been debated and explored amongst the team did a form begin to develop. The form responds to the change in perception as you embark onto it and cross the water. It is wide at each end with gently outward-sloping walls. As you move through it the bridge narrows and the walls tilt until they slope in. This allows you to lean on them. Gradually you are brought closer to the water. The narrowing and tilting of the space of the bridge creates a squeeze that subtly underlines the sense of extension out over the water.

STRUCTURAL CONCEPT

The bridge's walls provide an obvious location for the structural depth required to span the 55-metre gap between the quays. This decision ties the structure into the profile of the shallow arc of the deck as it crosses the river. The 1.4-metre height of the balustrade walls are not deep enough to span across as a simple beam. Something else is needed to give structural depth and therefore strength and stiffness.

Price & Myers thought of a solution used on an earlier project, the Dublin Millennium Bridge, which had similar constraints of site, span and deck gradient. The shallow beam created by the bridge balustrade walls is jointed to legs under the structure at each end. These legs combine with the beam to create a singular portal frame structure. This structure acts as a 'squared-off' arch and allows the beam and haunches to work together with a combined structural depth of over 4 metres between the supporting pins and the top of the structural balustrade. The bridge deck extends over the edge of the quay by around 3 metres and allows these legs to be hidden in underground chambers behind the quay wall.

1: The 75-tonne bridge suspended from the crane and ready for lifting out over the Floating Harbour.

2: Final checks on the fabricated structure prior to it being lifted by a 1,000-tonne crane.

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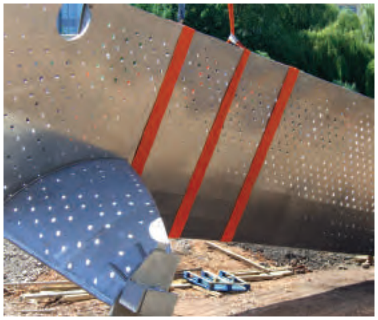

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3: The bridge was fabricated upside-down, laser-cut skin sheets are welded onto a skeleton of ribs.

4: The skin curvature is generally small, except at the ends of the bridge where the balustrade skews steeply down to the deck level.

5: The bridge in flight suspended from a 1,000-tonne crane over the floating harbour.

6: Manoeuvring a fabricated element of the bridge into position prior to welding the eight sections together on site.

7: View of the bridge haunches suspended above the reinforced concrete abutment chamber.

8: Exploded view of the bridge structure, showing structural skins in their skewed form, and the underlying skeleton of stainless steel ribs.

INTEGRATION OF LIGHT

The artist in the team, Martin Richman, works with the medium of light. How the bridge appears in different light conditions and how the structure itself is lit are key aspects of the design. The bridge is designed to be lit from within its 'body'. This means that its surface must have some kind of transparency.

Stainless steel was the immediate choice for the material of the bridge. Its surface is reflective and responds to changing light conditions. It can be perforated into a mesh to allow light out of the structure at night. The decision to have a perforated stainless steel surface to the bridge presented a dilemma. The skin could be a mesh cladding over an internal structure but this is no way to design a bridge that is conceived a singular object. The skin of the bridge is the structure. Like the drinking game with the tissue and coin, the perforations in the surface of the bridge need to be as large and widespread as possible without causing the skin to fail.

STRUCTURAL CHALLENGES

In order to understand the affect of the perforations on the structural skin, Price & Myers carried out some detailed research on the structural properties of metal panels with perforations. They studied the behaviour of plate samples under direct tension and compression loading as well as in shear. This led to an understanding of local stress increases around the holes and the affect on the overall buckling strength of the skin. From this the engineers developed a series of rules that governed the size and arrangement of the perforations across the surface.

By applying these rules to an iterative structural analysis process, a picture of the stress pattern across the bridge's surface began to emerge that enabled Price & Myers to determine how much material could be removed across the surface. As this process reduces the weight of the bridge structure the weight saving was fed back into the analysis model over several iterations to optimise the analysed stresses and hence the size of perforations.

A constant 6-mm skin thickness is used for the whole bridge. It is solid at points of maximum stress at the haunches and in the middle, elsewhere the analysis and optimisation process developed by Price & Myers allows it to be 'thinned out' with perforations that vary in size according to the stress levels in the skin around them.

UNDERLYING GEOMETRY

The form of the bridge is generated by a very simple cross-sectional shape. It varies in size, proportion and angle along the bridge to make a set of smooth, skewed surfaces that wrap around to create the structural walls and soffit of the bridge. A network of cross-ribs and stiffeners follow the form of the skin. Rods along the top and bottom of the structural walls provide a smooth transition between the structural surfaces of the bridge and concentrate metal at the most effective points in the structure. The deck itself has no structural skin, instead a network of bracing works with the rest of the bridge to create a closed 'torsion box' whilst still allowing access to the 'inside' of the bridge for maintenance.

The bridge's structural walls curve out and downwards at its ends to meet the hidden structural haunches located below the visible structure and housed in reinforced concrete abutment chambers. All surfaces of the bridge are linked together structurally, and importantly, are all developable to flat sheets to allow them to be accurately cut out and applied to the 3D form of the structure.

8

MODELLING & DRAWING THE BRIDGE

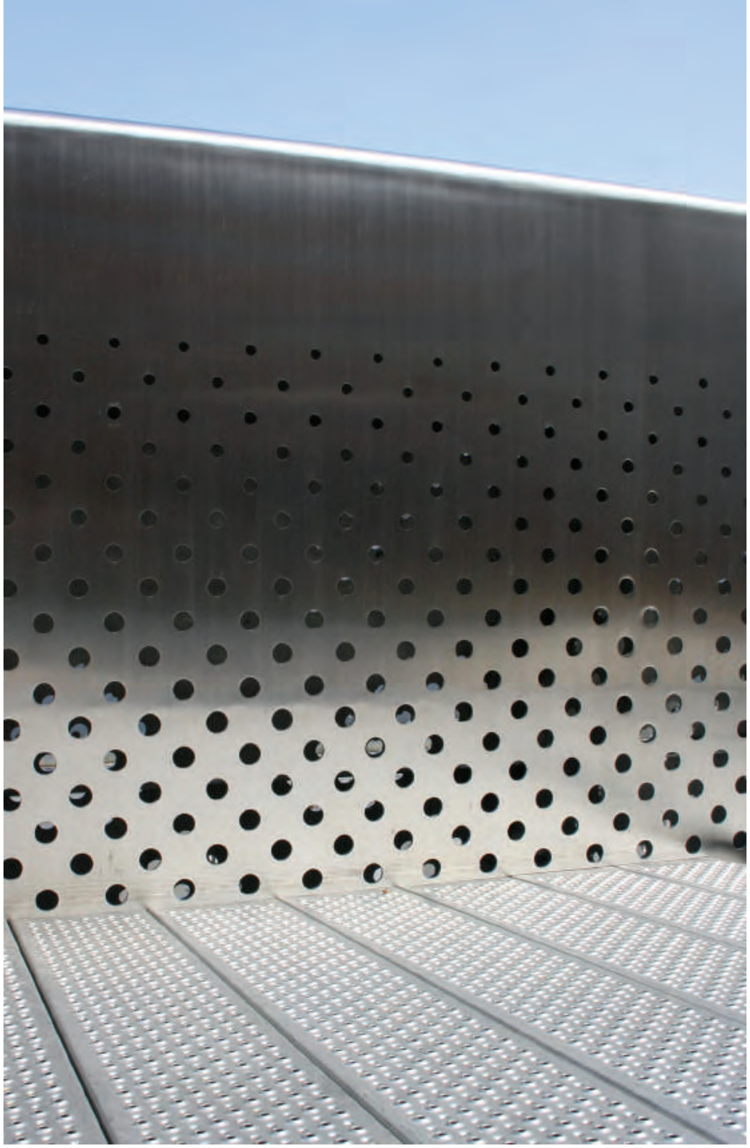
Price & Myers used Gehry Technologies' CATIA-based software, Digital Project, for the modelling of the structure. A parametric and semi-automated approach to the modelling was the only feasible approach to producing drawings to document the requirements of the design. The modelling of the form itself was relatively straightforward, the wrap-around skins were modelled as ruled surfaces according to the geometric principles outlined above. The more challenging aspect for Price & Myers was to find a way of drawing over 48,000 different-sized holes across these skewed surfaces.

The process of defining the perforations starts with a colour-contour stress diagram of the stresses across each skin. The engineers developed a specialist piece of software to convert these stress diagrams into a vast spreadsheet, giving numerical stress values for each pixel. The Digital Project model was developed using a parametric skin component representing a typical skin panel that would be fabricated. This panel, when copied across the surface of the model, changes its size and shape to suit the surrounding geometry of the bridge. At the same time it reads the spreadsheet to establish where it can put holes and what size they should be. The model then wrapped this perforated pattern onto the skewed shape of each skin panel to ensure holes did not clash with stiffeners.

FABRICATION

A fabricator based in Lancashire made the structure. It was far too large to contemplate moving in one piece so was fabricated in eight sections. Each section was made in a similar way. A skeleton of ribs was built first, using a jig to define their position. Corner rods and the perforated skin panels were welded onto the skeleton. The skew of the panels was generally small enough to enable the panels to be simply pushed into shape on the ribs and welded into place. At the ends of the bridge the curvature is more intense on the inner skins and the panels were pre-formed to the curvature needed.

The skin panels are split between the cross ribs. Adjacent skin panels and the intermediate rib were welded together using a single three-way butt weld.



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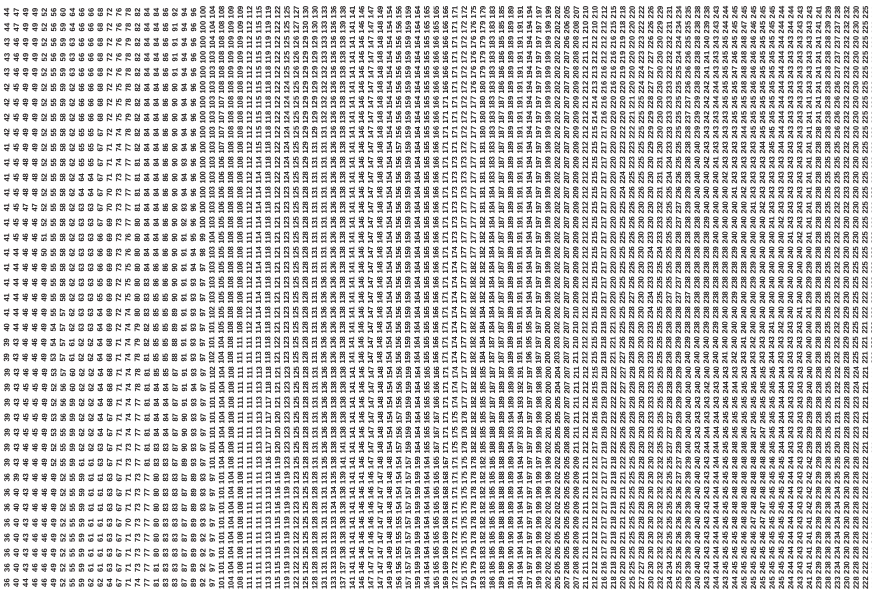


9: The completed structure reveals its perforated structural skin and underlying skeleton at dusk when it is internally illuminated.

10: Skin perforations.

11: A table of stress values generated from reading the stress contour plots is interpreted by Digital Project to determine the size and distribution of perforations across the skin.

This weld, along with welds to the corner rods, were ground down and polished into the surface to create a seamless stainless steel skin.

The units were transported to the site in Bristol for final assembly on a plot adjacent to the bridge site. They were placed on large steel trestles, aligned and welded together to create the overall 55-metre-long seamless structure. Lights were pre-installed at this time.

LIFTING

A very large 1,000-tonne crane was built on the site to lift the completed 75-tonne bridge from its assembly position and swing it around over the Floating Harbour. The structure was lowered down into pre-constructed reinforced concrete abutments in a matter of minutes.

CONCLUSION

The finished bridge looks very simple and, on first inspection, it can belie the complex engineering required to make it so. On closer inspection the observer can see the working of the bridge's internal and surface structure manifested in the perforated pattern across its surface, especially if they visit at night. It is one of the few structural stainless steel bridges in the world and has received awards from the RIBA and the Institution of Structural Engineers amongst others.

THE SPHERE GENERATE, CALCULATE, FABRICATE

OLIVER TESSMANN, MARK FAHLBUSCH, KLAUS BOLLINGER, MANFRED GROHMANN
& MARKUS SCHEIN, BOLLINGER & GROHMANN INGENIEURE

In 2006 Mario Bellini won the architectural competition for the refurbishment of the iconic Deutsche Bank towers in Frankfurt. The proposal was to construct a strong visual focus-point in the lobby in the form of a sphere, made from seemingly random criss-crossing metal strips, representing the fluid and dynamic core of the building.

The proposal was further developed by an interdisciplinary team of architects (Mario Bellini Associati S.r.l), engineers (Bollinger + Grohmann) and contractors (Arnold AG). The process of developing the proposal from conception to realisation is described in this paper.

GEOMETRICAL GENERATION

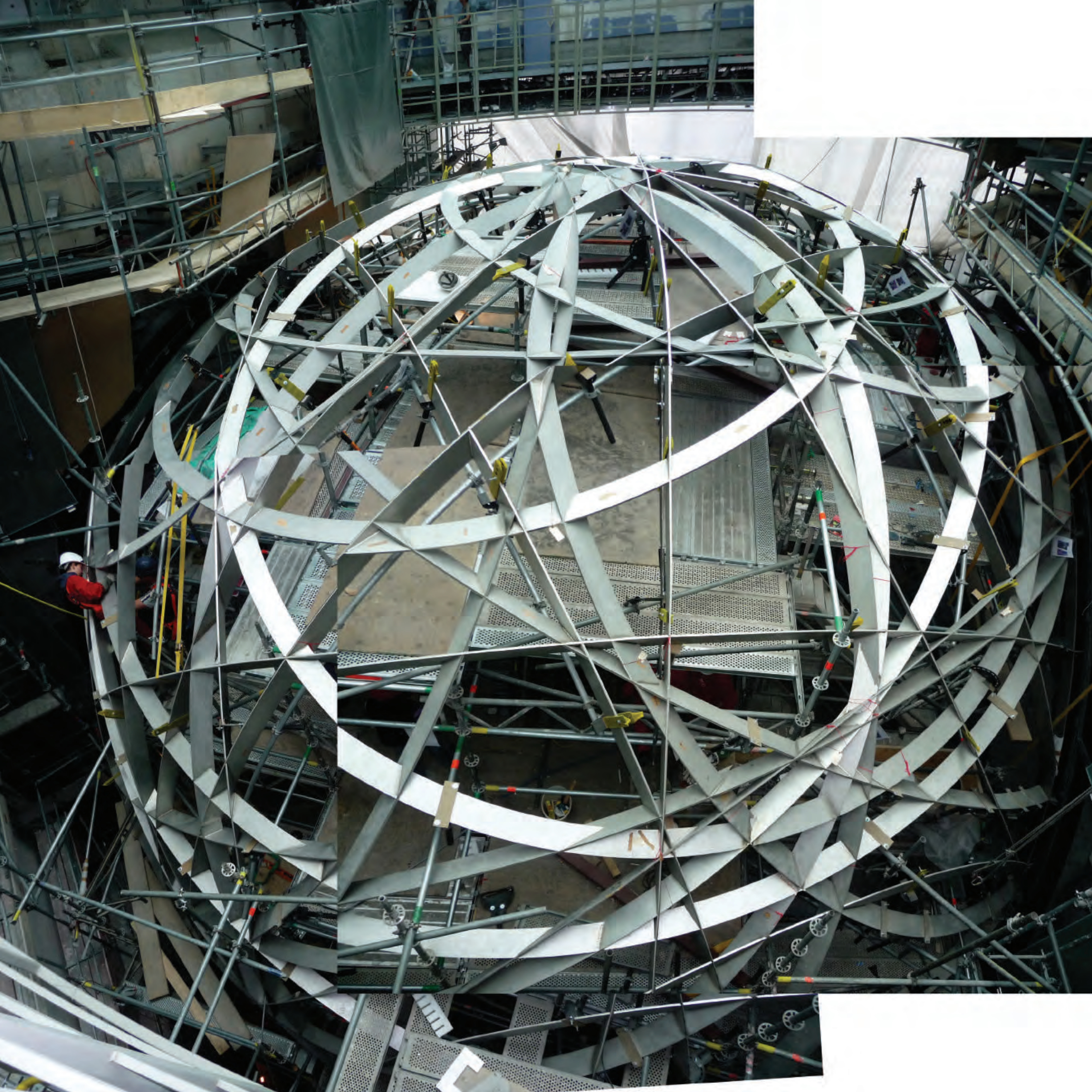
To develop a digital, geometrical model of the sphere, it was necessary to come up with detailed geometrical descriptions of the strips and their nodal connections, taking into account scenarios of manufacturing and assembly. A parametric design model, representing rings with various radii, which populate the virtual spherical surface with a diameter of 16 metres, was the starting point of the subsequent design phase. With three spherical coordinates defining a circle, a ring can be generated in two ways.

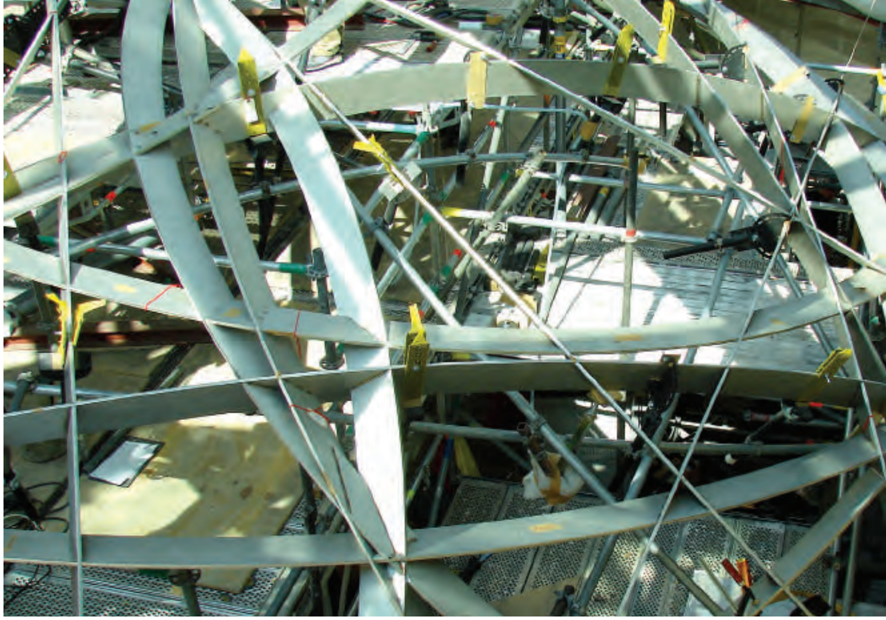
1. A ring is derived from a planar curve offset from the circle. A surface in-between the circles defines the ring. An extrusion of the surface forms a volume that represents a profile.

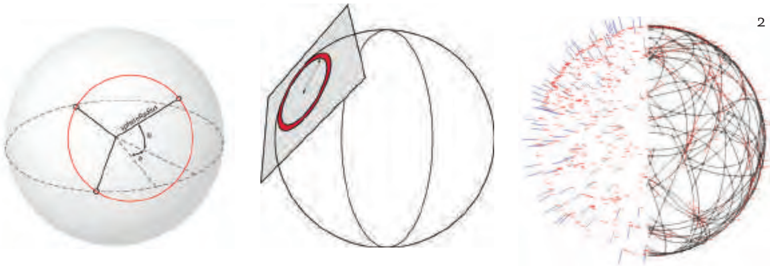
2. A ring as a cone segment, derived from a cone between the sphere centre-point and the circle.

The former version was chosen because it could be easily fabricated from sheet material whereas the second version requires unrolling the single-curved surface, which created more complex ring intersections.

The process of generating a virtual sphere started with a predefined number of rings. Thus the random appearance of the competition structure was maintained. Geometrical constraints had to be maintained throughout the generation process.







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1: The sphere close to completion.

2–4: Every ring is based on a circle and its planar offset, described by three spherical coordinates. Analytical models display nodes and joints as stingers and simulate the structural behaviour. Massive scaffolding and permanent surveying are needed to bring all elements into the final position. Assembly and welding took place on-site.

Each ring should have at least two nodes with neighbouring rings. The diameter of the rings should not go below a certain limit. The joints between the single strips should maintain a certain distance between each other to prevent tiny segments, which are digitally representable but impossible to manufacture.

EVOLUTIONARY DESIGN APPROACH

The number of parameters within the model presented a considerable number of possible solutions. To scan such a space manually would have been impossible. Thus the parametric model served as the basis for an evolutionary process that was able to negotiate geometrical parameters, contextual constraints and structural performance. A genetic algorithm with elements of island injection was implemented. All spherical coordinates of the strips of one sphere were represented as a binary string – the blueprint or DNA of each individual. Different populations have been generated with random individuals. Geometrical, contextual and structural constraints have been implemented as fitness functions:

· Collisions between the rings and the bridges should be eliminated. Any intersection would have involved cutting the ring and creating scary blade-like objects, close to people who walk in the bridge.

· The rings should be evenly distributed along the spherical surface. A requirement that opposes an optimal structural solution of a series of arcs that span between the two towers of the bank.

4

· Deflection – the most relevant structural criteria of the sphere – should be minimised.

Since the object sits inside the lobby of a building, horizontal forces could be ignored. Dead weight and deflection became the driving structural considerations. Sphere variations, with initially random ring configurations, were generated and evaluated. Every generation consisted of 50 individuals. The process of improving the parametric and evolutionary model went on until the most promising design was found (after 280 generations). Geometry generation and its preparation for geometrical and structural analysis proved to be very time-consuming but the automation of the process justified its use. A manual design process would have required an engineer and a modelling expert and would have taken more time.

STRUCTURAL DESIGN

The sphere intersects the two towers and is supported by them. The shape possesses a spatial shell-like structural behaviour. The dead weight is transferred through the rigid nodes to edge beams, which are fixed to the concrete walls of the towers. All rings are made from 200 x 15-mm-flat, stainless-steel bars. The structural analysis within the evolutionary design stage, and all subsequent phases, was carried out by a model consisting of nodes and linear elements. All intersection points between the circles were defined as nodes. Additional nodes were derived from segmenting circles into a series of discrete linear elements. Flat steel bars, with orientation towards the circle centre point, served as cross sections of the elements. The polygonal abstraction of the rings in the structural model provided a suitable approximation of the original geometry and reliable analysis results. The nodes and elements model precisely indicates the internal element forces and forces at nodes, which were necessary to specify the quality of the node details and the welding seams. Eight different kinds of welding seams were defined by the structural engineers, according to local forces and geometrical complexity. Rings with an almost horizontal orientation posed the structural challenge of bulging. Long vertical arc segments without any intersections tend to buckle, but structural performance was not the only criteria.

FABRICATION AND ASSEMBLY

The digital model for fabrication purposes accurately described the rings as intersecting volumes. At every intersection node one ring is split and the other one runs through. The distinction was drawn according to structural requirements and the material dimensions. Intersecting nodes with an angle smaller than 30 degrees causes problems during welding. These nodes had to be identified in the digital model in order to estimate additional costs and effort. Limited dimensions of sheet material required threaded connections of segments in addition to the intersecting nodes. These connections had to be calculated and sized according to the local forces appearing in the element. The amount of nodes and elements, and the various digital representations, demanded the development of additional customised scripting procedures to analyse geometrical properties and to synchronise the different models.

More than 1,400 ring segments were laser-cut from stainless-steel sheets. The intersecting nodes needed slanted edges, which were defined by the orientation of the ring on the sphere surface. This champher was milled after laser-cutting the segment. Every piece was individually labelled, packed and shipped. Prefabrication of sphere segments was not considered as an option. Tolerances of the existing buildings or within the sphere, due to assembly and welding, would add up. Bit-by-bit assembly, in contrast, offered more opportunities to equalise small imperfections. A 3D scaffold served as temporary support during construction. Before the sphere could act as one coherent structure every ring segment had to be held in precise position by claws. Preventing collisions between sphere elements and scaffold required a thorough planning of construction sequences. On-site the physical object was constantly coordinated with the digital model to control the current status of the construction. Thus, interfacing digital and physical realms became a constant task from early design to final construction.

CONCLUSION

Collaboration between the design team, structural engineers and contractor was never carried out in a linear fashion. New insights gained during workshop planning required a reconsideration of the structural model. In return, structural constraints caused changes in the geometrical model. To synchronise the different digital representations and maintain coherent models, customised scripting procedures became essential. These procedures transferred information and interfaced the different models. Designing digital tools became a crucial aspect of the overall design process.

THE AGENCY OF CONSTRAINTS

JOE MACDONALD,
URBAN A&O, HARVARD UNIVERSITY

The work of Urban A&O includes teaching, research and practice, and all three serve to contribute in significant and yet different ways to the projects presented here. Four operating principals describe the philosophy of our work: hands-on material exploration; the use of emerging technologies to design and fabricate form; multidisciplinary collaboration with artists, technologists, scientists and other architects; and, perhaps most significantly, the cultivation of social interaction and education through design within the public realm. All of the projects we take on occur within this public sphere, where we have the opportunity to test our ideas and forms within highly interactive and unpredictable public settings. Most significantly, we strive to seek out innovative research-based work, and by research we are referring to designed research, where we are actively shaping and designing formal, programmatic and content-based parameters of a project at the outset.

About six years ago, we made a conscious decision to focus exclusively on the capabilities offered by parametric modelling. This has been both a tremendous opportunity for us, and a considerably arduous process that has shaped the identity of Urban A&O as well as our praxis in relation to what we observe on the contemporary architectural landscape. The title of this paper 'The Agency of Constraints' may sound contradictory, but it very much describes the underlying premise of our work. By constraints we are referencing parametric modelling nomenclature – numerical and geometric parameters – and our desire to actually design those parameters in highly creative ways. That's where agency or potential – or promise – comes in. While parametric software allows us to precisely define the project's governing constraints, we very much welcome and embrace unanticipated events along the way. Since we can't predict the formal outcome of the work during the early stages of research, the choices we make when formulating project parameters are not only highly speculative but also tremendously important. We have to live with these early choices – either for better or worse – as the life of a project advances. The parameters define the boundaries and the shape of future design choices.

The biologist Conrad Hal Waddington's work 'Evolution in Four Dimensions' is a visualisation of what he calls an epigenetic landscape, and it demonstrates our point

about decision-making in design and the massive effects that decisions – or to Waddington, mutations – have on design output: which way is that ball going to roll? Epigenetics refers to the mechanisms for transmission of information from a cell to its descendants, or how gene regulation determines development. If we look carefully at Waddington's visualisation to understand what is affecting this landscape of decisions, we see a network of competing and, quite often, contradictory parameters that shape the fate of that metaphorical ball on the landscape above.

Clearly all design projects bring with them their own set of associated parameters: client, site, budget, codes, etc. What ups the ante for us is the opportunity to introduce an additional set of carefully designed parameters geared toward generating new links, new connectivities and new relationships that are not necessarily stated in the project brief. The emergence of these properties offers an unprecedented interaction between intrinsic geometric, structural and material qualities, on the one hand, and conscious form-making on the other. This is the territory we aim to occupy with our work.

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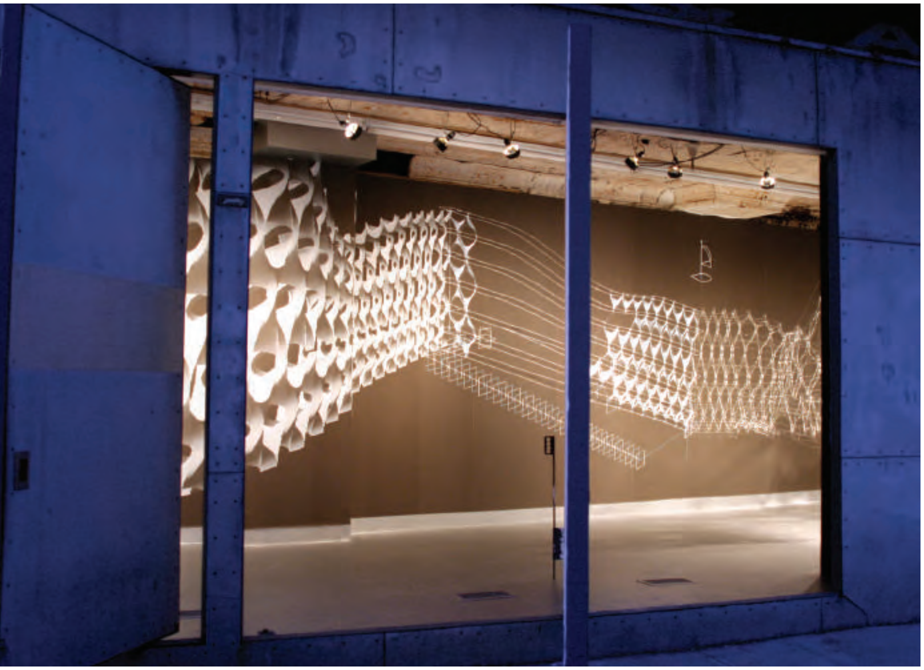
STRUCTURED ORNAMENT: BONE WALL

What constitutes a pattern? Visual recognition? Geometric uniformity? Behavioural repetition? What happens when we move to higher orders of complexity in physical organisation by including emerging developments in computational recursion and parametric modelling? Continuity and connectedness, two indicators of topological form, are intrinsic to nearly all digitally generated patterns. Simply put, pattern is technological, and the logic of pattern-making is not simply 2D; they also break into 3D, whether in composite textile fabrication or skeletal framing assemblies in which terms such as 'tiling', 'nesting', and 'tessellation' describe the particular parameters and operative rules of the formation of pattern.

Parametric design processes begin with the definition of meaningful parameters and control limits. Iterative feedback loops generated by the system's designer through programming, master geometries and built-in evaluative criteria allow for indexical control points and material optimisation. At the same time, the ultimate regulation of these properties and the generation of form require the designer to maintain a fully participatory role and interaction with the system throughout the design process.

In this interactive relationship between the designer and software, what are the technological implications of a pattern's cell generation and its repeat formulation, a network of smart relationships, as they relate to the production of architectural morphologies? Simply put, parametric modelling and physical prototyping, at a variety of scales, allows the designer to explore a broad range of potentials for the creation of new forms in architecture. In this exploratory process, the logics of pattern can be integrated at multiple design thresholds: in initial creative concept models, in generative spatial armatures and in contemporary CAD/CAM fabrication techniques.

Within the site of pattern-making, BONE WALL explores the relationship between surface and depth. Preoccupations in current architectural practice about the seemingly limitless effects of a building's 'skin' as a material artefact have relegated this surface as the primary domain of creative interest. Often the singular focus of the architect, it has become an ever-increasingly thin site of performance. As a result, this emphasis on surface has arrested our understanding of space at the building envelope. Pattern, for all intents and purposes,



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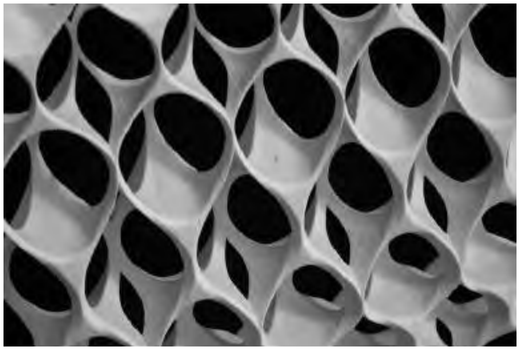

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1: BONE WALL on display at Storefront for Art and Architecture, New York.

2: BONE WALL in profile.

3: Wallpaper collage of CATIA screenshots of BONE WALL in development at Storefront for Art and Architecture, New York.

4: STL print of the wall's base cell pattern.

remains an extrinsic and 2D application. A counter-argument to this trend, BONE WALL demonstrates through geometry, structure, materiality and spatial configuration that pattern can in fact be multi-dimensional, intrinsic, programmatic and capable of occupying complex spatial geometries and substantially deep space.

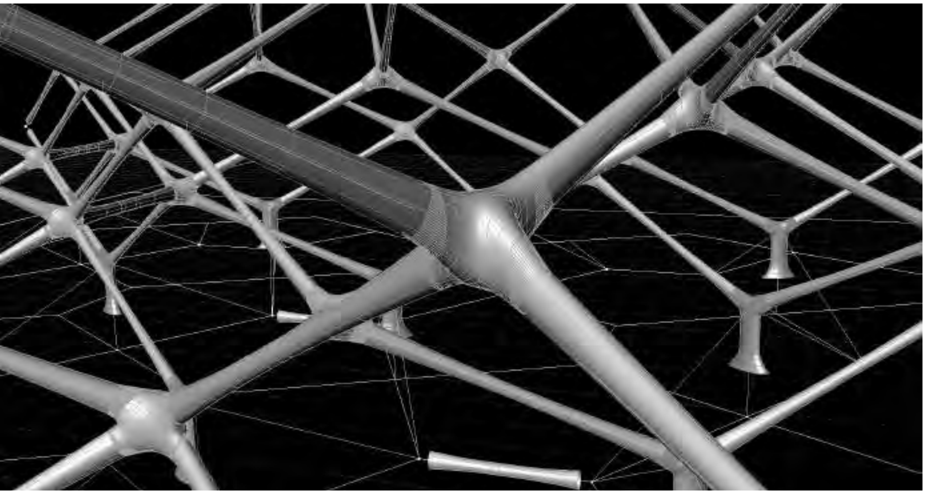
DESIGN METHODOLOGY

BONE WALL is derived from a single-base cell that is modulated, rotated and repeated to construct a volumetric form. The CATIA 'part file' of the base-cell component, along with its generative parametric modelling constraints, is the origin from which all cells depart, according to the CATIA 'product file' which shapes the overall wall armature of BONE WALL.

The ambition of this experiment was to explore continuity of surface and modulation of light within the wall, in addition to providing programmatic elements such as storage and seating for the human body. The design of BONE WALL began with parametric modelling of the base cell, or rather a half-cell, which was then inverted 180 degrees and rotated 180 degrees to produce a complete cellular unit. The base cell has six triangular 'horns' – three up and three down – with a total of 18 corners, or 'control points'. Through iterative manipulations of these control points along the wall's organising horizontal splines, as configured in CATIA, the body of the wall and its cellular web-like structure stretches and undulates. Any change made to the geometry of the splines regenerates the shape of each cell, demonstrating the non-linear and reciprocal relationship between software and designer that is intrinsic to parametric, or parameter-based, modelling.

We used CATIA's 'product-file' structure and 'part-file' cell in context modelling to establish geometric dependencies, whereby modifications to the form of the wall would propagate down CATIA's hierarchical tree and update affected cell geometries along the way. A total of 72 full cells or 2,592 control points were 'powercopied' to comprise the complete wall. Parametrically linked, all the control points 'know' the relative location of one another at any time in the design process, allowing the designer extraordinary control of the project in interaction with the software.

Five variable cells were arranged on a 4 x 8 x 1/4 ft. sheet of 15-lb high-density foam. Each cell is divided into three parts in Rhinoceros, to be exported as an IGS file for CNC-milling.



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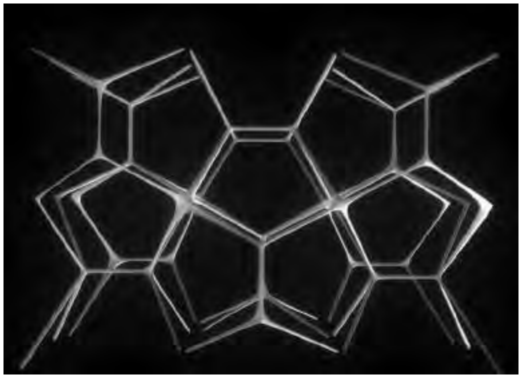

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5: Struts and joints of Radiolarian Project.

6: The space-frame of Radiolarian Project in formation.

7: The 18-ft-tall STL 3D print of Cairo Tower.

FABRICATION AND ASSEMBLY

The cells were fabricated on a three-axis CNC milling machine in high density foam. Upon close inspection, the router's tool path can be seen on the surface of BONE WALL. It is not entirely smooth to the touch. The milling machine was set on a 1/32-in. step-over, resulting in a topographic plan-like finish. The cells were then joined together with adhesive by hand, and the final wall was painted following assembly.

In its use of parametric modelling, BONE WALL is an experiment aimed toward the advancement of contemporary architectural practice. Parametric modelling environments shape new cognitive ambiances within which design procedure is conceived. BONE WALL is not only an exploration of pattern and volumetric form; its execution also demonstrates a new opportunity for designers to participate more directly in processes of fabrication. In our contemporary architectural context, a resuscitated debate over the role of ornament is unfolding; BONE WALL strives to demonstrate ornament's intrinsic necessity over extrinsic contingency.

RADIOLARIAN PROJECT

When considering structure for a three-story pavilion, we explored the 3D potential of a 2D pattern: the Cairo hexagon. Comprised by an arrangement of four pentagons, we folded the Cairo along its pentagonal seams up into a version of a space frame. Typically space frames are deployed as roof structures; our ambition was to deploy a space frame throughout the building as if it were a rectangular sponge. The folded parametric wireframe of the Cairo pattern structure serves as the foundation of the constituent assembly. The points and lines of the wireframe are used as parametric power copy input geometry for two types of components: struts and joints. In order to accommodate the multiple relationships between the struts and joints, three strut versions and eight joint versions were developed and deployed throughout the armature. A series of formulas define the elliptical profiles of the strut components. The joint components respond to and are tangential to the strut components, allowing for a homogeneous structure.

CAIRO TOWER

We would like to conclude by presenting an ongoing research project where we have become interested in the possibility of radically vertical configurations in parametric modelling. A recurring pattern in our office is the Cairo pattern, where four pentagons combine to comprise a hexagon. The streets of Cairo are paved with stones of this geometry. We began this investigation by taking a closer look at the potential of this 2D geometry, with the intention of breaking into the 3D. After some geometric experimentation with this figure, we constructed a form that was faceted in all directions.

In turn, scalar variations of that form can be stacked and nested into a tall, stable column of volumes as represented by wireframe in CATIA. Upon examination, the wireframe anticipates what will become two basic components: struts and joints. When those struts and joints are thickened, the Cairo Tower begins to take shape structurally, and what evolves is an assembly where no two components are exactly alike. The twisting joint details are of particular interest.

Our office recently won an award for Best New Practice in New York from the American Institute of Architects and we were asked to exhibit a model that would occupy a 2 x 2 x 18-ft space. We began to modify our design of the Cairo Tower for this space. As we moved to fabrication, we decided to 3D-print the tower. Prior to 3D printing, the tower went through various analyses in the engineering software program, SAP, where a series of subsequent modifications were made. The Cairo Tower is a case study into the structural possibilities that could generate a tower at the scale of the city.

In summation, we have attempted to present built work that demonstrates, through parametric modelling, what we call the agency of constraints. Of course these are designed constraints without which form cannot be realised. Above all else, we are advocating an immersive and reciprocal relationship between the designer as an active author and informed participant in the deployment of a very powerful tool that promises new forms, new experiences and new processes for near-future architectures.

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THE RICHMOND SPEED SKATING OVAL ROOF

GERALD EPP – STRUCTURECRAFT BUILDERS, FAST + EPP STRUCTURAL ENGINEERS,
LUCAS EPP – STRUCTURECRAFT BUILDERS & SANTIAGO DIAZ – STRUCTURECRAFT BUILDERS

The Richmond Speed Skating Oval hosted the long-track speed skating event at the Vancouver Winter Olympics in 2010. Now in legacy mode, it contains two ice rinks, eight gymnasia, a running track and a fitness centre. To accommodate the large speed skating track, the roof has a clear span of over 100 metres, creating a building footprint of 25,000 square metres. Cannon Design's vision for the building's feature roof focused on the overall exterior form, allowing the structural engineering and design-build firms involved the freedom to explore and innovate in the detailed implementation of this form in consultation with the architect.

Viewed from the exterior, the roof is a continuous flowing surface, peeling off from the facility to symbolically reference the feathers of a heron, the official symbol of the city of Richmond. From early on in the design a desire to showcase timber, where possible, was expressed both by the client and design team.

Primary composite glulam-steel arches were proposed by the design team, nestled in the trough formed between each of the 14 swooping bays. A significant secondary structure was required to span between each arch, leading StructureCraft Builders, in conjunction with Fast + Epp engineers, to research, develop and propose for this secondary structure a unique modular scheme.

The resulting all-wood roof utilises dimensional lumber sourced from local pine-beetle affected forests to create 'WoodWave' panels, each spanning up to 13.1 metres between the 15 parallel primary arches. The geometrical pattern formed by these panels on the underside of the roof highlights the timber solution, which is with few precedents on this scale. Variation in module design was captured using parametric models, and linked to a computer-controlled manufacturing system, creating a full-cycle digital fabrication process.

A fluid link between architecture and structure allowed a two-way design process, with structural systems informing and being informed by the global form of the building. The result is a seamless integration of structure, function and form: the exposed structure simultaneously creates a singular aesthetic while incorporating acoustic absorption and pre-installed services.

1: The dramatic entrance to the Speed Skating Oval, featuring exposed timber WoodWave panels.

2: Machine-pressing the strands into their arched shape, forming a 'V' truss.

3: A cassette of 13 dimensional lumber strands.

4: An assembled WoodWave panel comprising three 'V' trusses.

5: Internal bays of the WoodWave panel span between the primary Glulam arches.

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MODULAR DESIGN

Several constraints naturally led to the application of a modular approach to every aspect of the WoodWave panel design and fabrication. The necessity of opening in time for prescribed event-testing before the 2010 Winter Olympics imposed a tight programme on the project, moving from design conceptualisation to erection on site within 20 months, including an intensive 12-month period of research, development and testing. Timber as a component of construction is typically quite small; assembling many timber pieces into much larger modular components off-site allowed time on-site to be minimised. Despite the inherent complexity and numerous variants of the module, the assembly-line-style fabrication process benefited from the large number of panels.

StructureCraft's involvement as a design-builder led to a natural desire to create efficiency (and hence profit and risk-reduction), which manifested itself in several

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ways throughout the design and fabrication process. The design-build process creates an environment conducive to modular design: similar to the manufacturing industry, the entire process of conceptualisation, design, modelling, testing, fabrication and erection takes place in-house, allowing each step of the process to be influenced by the other steps. The end result is a solution which is efficient as a whole system, not just comprised of individually efficient parts. The choice of an arch structure for the WoodWave panel created structural efficiency, while also forming the pillowed appearance of each roof bay. The challenge was to create this arch from timber, and allow hidden integration of services – sprinklers, ducts and lighting – while achieving the required acoustic and fire performance.

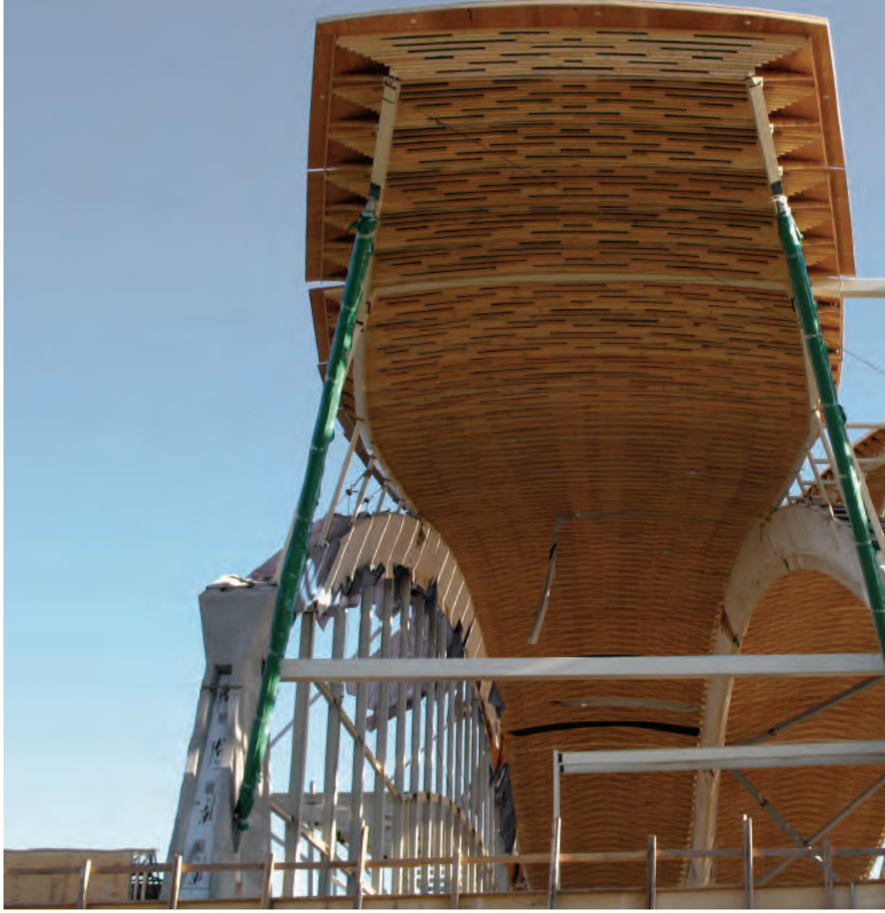
A timber arch requires significant depth to create structural efficiency, and is typically solid. Breaking down this solid form into an aggregate formed of much smaller elements allowed each element to be placed where needed structurally, and left the remainder open for service integration. The topology of the panel thus created took a unique 'V' shape in cross-section. The elements chosen were 2 x 4 in. dimensional lumber strands – conventional light lumber commonly used in wood frame construction throughout North America. The aggregate system of cascading 2 x 4 in. strands was made composite with strategically placed splice pieces, creating a straight 'V'-shaped truss; the truss is bent about its strong axis to form a structural arch.

As the unique design of this panel was without precedent, a detailed and extensive testing regime, comprising structural analysis and modelling, connection testing and full-scale prototypes, was undertaken to ensure that the behaviour of the panel was fully understood. The crucial splice connection between 2 x 4 in. strands was tested, and 14 full-size prototypes of the final WoodWave panel were built, tested and used to calibrate the structural analysis model. Geometry for both the structural analysis and fabrication of the prototypes was linked to a digital prototyping process, allowing the aesthetic effects of each design iteration to be assessed and considered.

DIGITAL MODELLING

The global geometrical principles of the project were set out and agreed early on with the architect. A parametric geometry model of the overall building geometry implemented each of these principles and provided a framework within which to create more detailed solids models of the WoodWave panels. Creating an associative and parametric solids model of the WoodWave panel allowed each 'instance' of this panel to respond to the different constraints imposed on it, and allowed changes in global form to be easily accommodated and reflected down to the smallest level of detail.

This model evolved over the length of the project, becoming a true Building Information Model (BIM). Alongside the geometry base, an embedded parameter database was developed, which incorporated additional information key to the creation of each panel's design. Structural parameters included panel length, load paths and splice connector layouts; details of services integration, building envelope considerations and acoustic design factors were also embedded. For each panel, these parameters were calculated from rule-based equations linking global geometry and position to the designer's requirements. As wood is a poor acoustic material (it reflects sound), openings were needed between the splices connecting each 2 x 4 in. strand,



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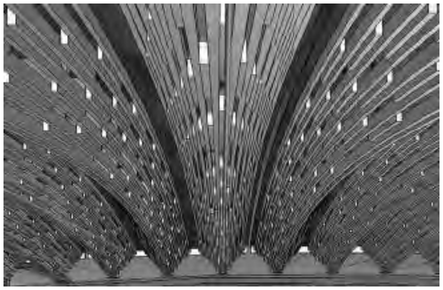

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6: WoodWave Panels stacked, prior to being shipped to site.

7: 3D parametric solids model.

8: First bay of the roof structure, fully erected.

allowing sound to be captured by the acoustic insulation layers on the inside of the panel. Conversely, structural requirements demanded certain splice configurations and lengths. A finely balanced set of rules ensured each panel's geometry developed adequate acoustic and structural performance. Due to the nature of timber as a material and, in particular, the constitutive behaviour of the aggregated 'V' truss, it was deemed impossible to accurately predict the exact geometry of each truss when bent. Each truss was thus fabricated slightly long, bent and then cut to length, ensuring accuracy in the final bent state. The parametric model contained both 'states' of each panel – pre-bending (straight, prior to cutting) and post-bending (arched and cut to length), allowing accurate dimensional checks to be performed at each of the manufacturing stages.

Comprehensive part numbering and component scheduling within the model provided accurate material take-offs, allowing each design change to be informed with an associated cost. This information was used towards overall panel-design optimisation (maximum

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structural efficiency with minimum material usage) and site erection process. Frozen solids models of each panel design were available at every point during the project, facilitating a beneficial link between design and every other facet of the design-build process. The final roof geometry comprised more than 500 WoodWave panels, each one of 55 unique panel variants.

DIGITAL FABRICATION

The modular panel design was realised through a complex off-site fabrication process, allowing for excellent quality control and creating a consistent product, while maximising efficiency. Several key challenges were encountered and overcome while creating and implementing this digitally controlled fabrication process. To create these unique panels, each 2 x 4 in. strand had to be precisely the right length and placed in exactly the right location in relation to each of the other strands in the panels. A total of almost half a million pieces of 2 x 4 in. needed to be cut, assembled into 20,000 strands, and built up into 1,500 cascading 'V'-shaped trusses, which formed each of the 500 WoodWave panels in the roof. To process and assemble this large number of pieces manually would have taken an excessive length of time and the precision required made it impossible to rely on the accuracy of manual work.

A custom digitally controlled manufacture and assembly process was created, incorporating custom computer, numerically controlled machines. A 'strand-builder' machine with two stages was fed solid timber in stock lengths at one end and cut, screw-reinforced and connected them into the correct length strands, using splices to connect individual pieces. Thirteen of these strands were then placed as a cassette into another custom-built machine, which pressed them into the arched, inverted 'V' shape, holding them there while each strand was fastened together and the steel tie rod attached. Two or three of these 'V's' were placed adjacent to each other and attached with a plywood diaphragm to form a WoodWave panel.

The parametric solids model virtually 'fed' the machine cut-list with both cut lengths and assembly location information. Custom scripts were developed in-house to link the digital solids model to the CNC machine assembly line. Detailed fabrication drawings of each panel were created using a largely automated process. These informed a comprehensive quality-control process and provided information for the non-automated elements of the process. The key to successfully creating and implementing this digital fabrication process was to strike a balance between automation and manual assembly: the cost to automate the last ten per cent of the process could cost a disproportionate amount and take much longer to implement. Throughout the design of the system, tolerances and imperfections were carefully considered and accommodated – CNC often brings false hope that everything will be perfect. Incorporating a natural, once-living material such as timber into a tight-tolerance mechanical system demanded consideration of its inhomogeneous and non-static properties (creep, shrinkage), and allowance for tolerance in every process.

The fabrication process thus created was refined over a period of months, with a production rate of four panels per day being reached. These panels were stored off-site and transported as needed to site, with the erection process overlapping fabrication. The fabrication and storage sequence was closely linked to the erection sequence, ensuring that panels were available as and when needed. Panels were installed on-site at a rate of up to 16 panels per day: one site crew landed and secured each panel, while a concurrent crew followed behind installing infill plywood stitching between panels to create the complete roof diaphragm. The accuracy in fabrication ensured each panel slotted in within tolerance along the doubly-curved geometry of each bay, with site tolerances being allowed for by the use of slotted holes in the bearing plates at each end of the arch.

Throughout this project, the consolidation of engineering, master craftsmanship, planning and design took place more often than not within a digital context, be it fabrication models, structural analysis models or design detailing. The physical proximity of the designers and fabricators in a design-build workshop created a unique atmosphere, constantly ensuring a balance and integration of digital/automated processes and more traditional methods. The realisation of this level of complexity in design would not have been possible without the utilisation of advanced digital tools up to and beyond their original capacities.

THREE PROJECTS A COMPARATIVE STUDY AL_A

As a practice, AL_A have a passion for operating at the intersection of design, technology and materiality. The blurring of these boundaries not only defines the work they produce, it defines the very way in which they work. Recent advances in design and fabrication technologies, in particular scripting and associative modelling, BIM and CAD/CAM fabrication, have fundamentally altered architectural practice. However, it is only when these technologies are used together with clever conceptual thinking and imagining, that they are transformed from being merely tools that automate production protocols. When the power of new design technologies is harnessed with creative and intellectual rigour, the results are authentically innovative.

This paper documents three of AL_A's recent projects. They are of hugely different scales but each one explores a new fabrication process and has broadened their way of thinking and designing.

HILLS PLACE, LONDON

Lack of daylight in the narrow streets around London's Oxford Street is a key issue in their underdevelopment. Hills Place provided a great opportunity for an innovative architectural intervention that would draw attention to the redeveloped office building from the major retail artery that is Oxford Street. Inspired by the artwork of Lucio Fontana, AL_A slashed the aluminium skin with large glazed areas orientated towards the sky to maximise and channel the natural light into the office space. The double-curved geometry of this facade is achieved by looking outside of the traditional building trades and appropriating techniques from the ship-building industry.

The facade is composed of a system of curved profiles that are connected together on-site, a technique used in the production of high-quality ship hulls.

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1–3: Hills Place London: aluminium facade off- and on-site assembly.

4–5: Hills Place London: preliminary experiments with variable mould concept.

6: Corian super-surfaces installation: optimisation constraints to maximise material use efficiency.

7: Corian super-surfaces installation: rationalisation constraints to ensure material compliancy.

Similarly, the metallic silver finish is a high-performance durable paint developed for super-yachts. Both the design and construction of this facade was the result of a collaborative process with Austrian ship-builders, Pinical. By making an undulating double-curved skin using flat sections AL_A have created a visually complex and faceted skin. This faceted surface exploits the play of natural light by fracturing reflections of passing traffic, which animate the enigmatic form of the building, making it highly visible from Oxford Street.

The facade is composed of a bespoke system of 1,500 140-mm-wide extruded aluminium profiles 7 metres in length that were cold-formed and mechanically bent using a machine controlled by hand and compared to templates derived from the digital model. The aluminium extrusions form a tongue-and-groove system, with rubber gaskets ensuring water-tightness and construction efficiency. These pieces were then individually assembled on-site starting from the top floor, but with each floor being installed from the bottom up, due to its interlocking nature. AL_A adapted a boat-building system, where the panels are normally fixed from the inside to a clip system from the outside. AL_A's 3D model became the tender document. The geometry was then adjusted back and forth in conjunction with the contractor to work with the constraints of the boat-building system.

The sculpted interiors of the windows were constructed by Windsor Workshop, who specialise in theatre and film-set design. They fabricated a CNC timber-ribbed frame covered with 6-mm flexiply from our 3D model. Areas requiring tight curvatures were created using polystyrene blocks hand-shaped on site. The whole

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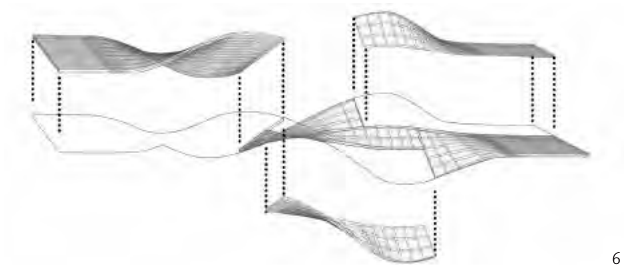

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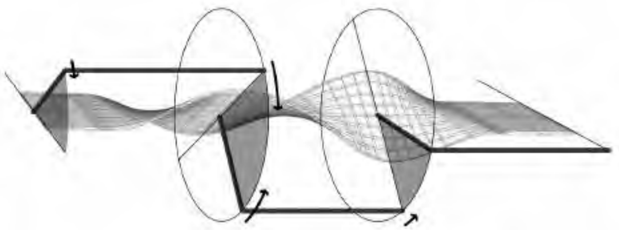

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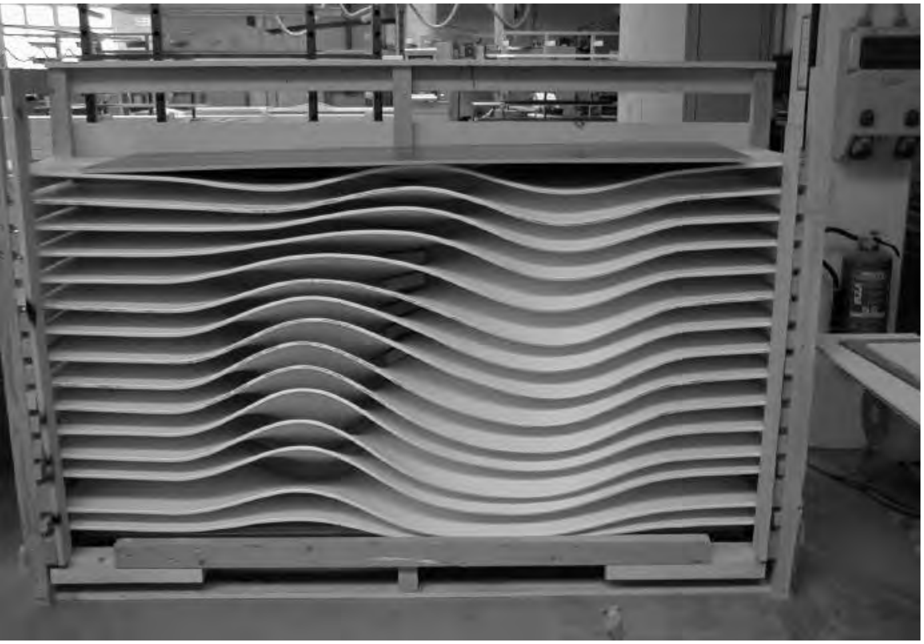
surface was covered in coaxial fibreglass matting, coated in plaster and Sto render finish to provide a smooth, durable, seamless surface.

CORIAN SUPER-SURFACES INSTALLATION, LONDON & MILAN

A recurring theme in AL_A's work is the repetition of motif – taking a single identical motif and working it to create visual and technical complexity. A drop of water creating a series of ripples became the metaphor for transforming space through movement. The Corian Super-surfaces installation exemplifies AL_A's drive to explore space, form and materials at all scales. The installation was a result of the team's desire to reveal Corian as a single-surface material rather than the monolithic block as commonly presented.

From the initial concept of a drop of water causing the visual repetition of ripples on a surface, the project grew beyond a design of visual and technical complexity into the creation of a system that manufactures the material. Together with the fabricators AL_A designed a system that could create infinite twists in form using the minimum materials possible. The influence of the efficient use of material was also coupled with the economy of budget, with no wastage and with all off-cuts re-used in the creation of the installation.

More than just an expression of the material, the surface transformations push the technical possibilities of Corian by exploiting its pliability and using the twisted geometry of the sheets to achieve structural integrity.



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8: Off-site pre-fabrication
of components.

9: Corian super-surfaces feature wall
and benches, Milan Design Week, 2009.

Advanced digital technology was used as part of the process for generating the design as well as for the fabrication of the installation. The realisation of this project is the integrated dialogue between experiment, design and fabrication. AL_A designed not just the piece but the way of making it, working closely with Hasenkopf to develop a single adjustable jig that created multiple twisted surfaces from a standard flat sheet.

This dialogue was facilitated by parallel design experiments conducted by AL_A (geometric), DuPont (material) and Hasenkopf (fabrication). In AL_A's London studio, parametric models were developed in the Grasshopper plug-in for Rhino to both generate and control geometry, while in DuPont's factory in Brussels physical experiments were conducted to test the pliability and material properties of thermoformed Corian, and in Hasenkopf's workshops in Bavaria an innovative variable mould was developed for the fabrication of unique panels from a single mould. Due to the curvature required, in some areas conventional timber moulds were also used, and were CNC-milled direct from Rhino files.

The geometry was rationalised to reduce the number of moulds and the surfaces of the 3D model were embedded with two layers of constraint. Rhino surfaces were modelled with two offset surfaces indicating the thickness of the material, with the inner surface being constrained to fabrication parameters (tightness of radii, extent of twist, etc.) while the outer surface was constrained to the visual performance (design intent) of the surface. In all instances, the exchange of data between experiments was done exclusively through Rhino 3D models. The end result was a fully parametric model that was able to control and constrain geometry through a combination of visual, material, and fabrication constraints and ultimately became the data issued from file to factory for both the off-site fabrication and on-site assembly.

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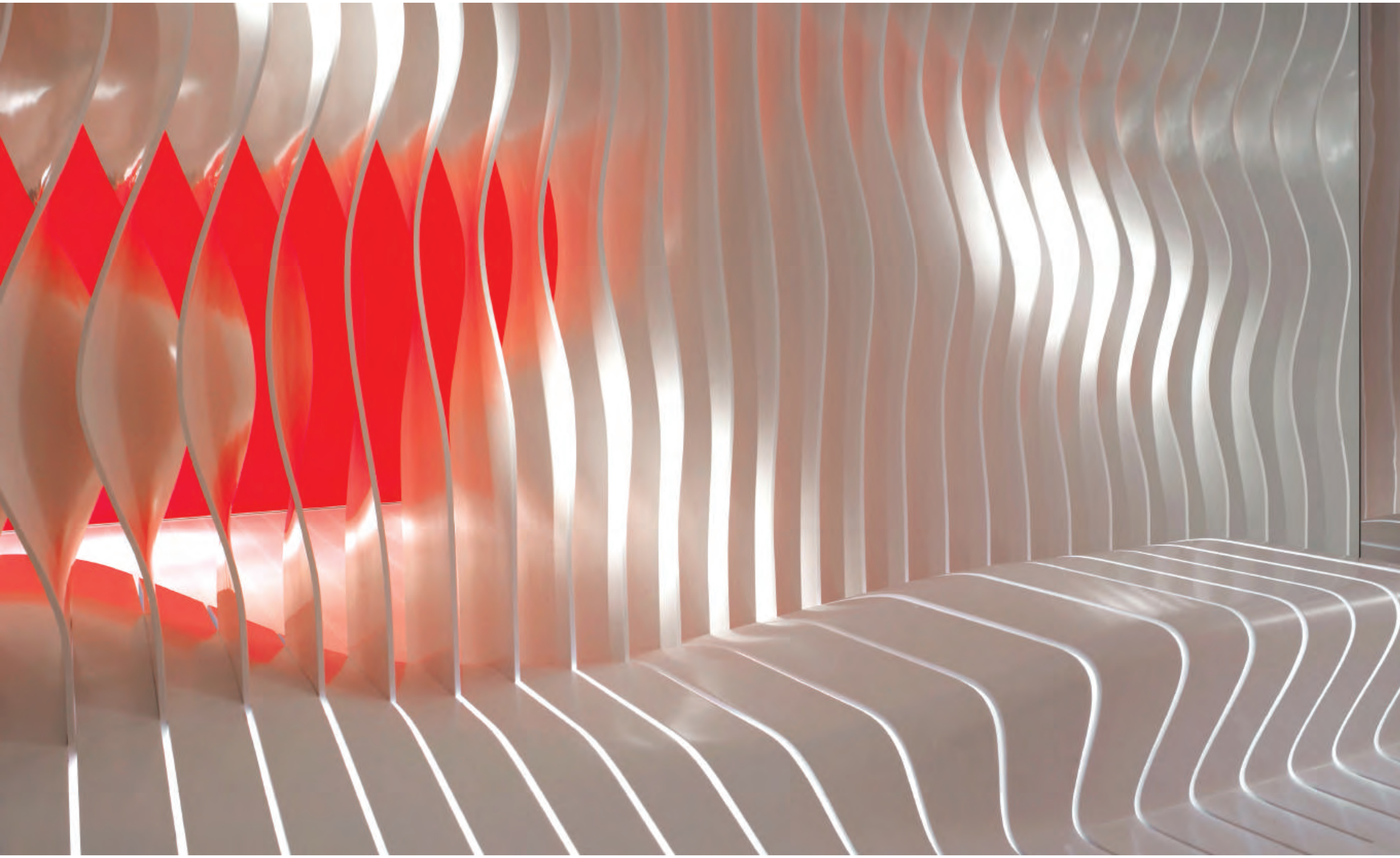

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BANGKOK CENTRAL EMBASSY, THAILAND

Located within the gardens of the British Embassy on Ploenchit Road, Bangkok's primary commercial artery, the project merges a seven-storey luxury retail podium and a 30-storey, five-star hotel tower into a cohesive and sinuously twisting form. The remarkable form wraps around two vertical light wells, as internal spaces open up to reveal stepped terraces and vertical gardens. It rises up from the podium facade, dividing hotel functions. Private guest-related programmes face the tranquil gardens of Lai Nert Park, while the hotel bar, reception lounge and sky terrace face the bright lights of the city centre.

Drawing on motifs and patterns found in traditional Thai architecture, the external skin is characterised by an assembly of extruded aluminium rainscreen, to create a dynamic pattern in response to external conditions. The irregular distribution of varying shingle types within a regular grid creates a moiré-like pattern, articulated by the play of light and reflection along the surfaces of these varying profiles. This rich and stimulating pattern visually emphasises the wrapping form of the building as well as providing scale and texture to the extensive opaque frontage at podium level. All glazed areas are designed to merge seamlessly with the aluminium skin.

The design of the cladding responds to the particular socio-economic condition of Bangkok, the inverse of that in the West, where labour is relatively cheap and technology very expensive. Advanced digital design processes were used to define a complex array of extruded aluminium shingles, requiring an intensity of manual labour that would not be viable in other parts of the world.

AL_A needed to use a minimum number of extruded components of varying length to create maximum visual complexity in order to meet stringent cost constraints. AL_A therefore limited the number of shingle types to three but used the application of a parametric model in Grasshopper, as a Rhino plug-in, to fine-tune generative parameters as a means of visually optimising and evaluating the pattern. The activation process shuffles the state of each component according to defined rules that allowed them to test a large number of configurations before fixing the pattern of the building skin. 2D AutoCAD files of each profile were given to the fabricators from which they CNC milled the extrusion dies. AL_A's 3D Rhino models were unrolled to produce component distribution maps that the contractor is used to set out the exact location of each component type.

CONCLUSION

The advent of digital technologies as tools for both design and fabrication has given AL_A great freedom in form-making. However this new-found freedom comes with great responsibility – the seductive quality of empty form can never replace the integrity and ingenuity of carefully developed concepts. All three projects within this paper are united by shared intentions: to merge the digital with the handmade, to produce visual complexity through the simple distortion of repeated elements and to bridge the gap between the act of designing and the act of making. The fusion of technology, creative thinking and the handmade continues to drive the work of their practice.

10: Bankok Central Embassy.

11: 1:1 profile mock-up.

11

MULTI-SPHERICAL MIRRORED SCULPTURE

CHIARA TUFFANELLI,
ARUP

This paper describes the geometrical studies underlying the design and manufacturing of Anish Kapoor's *Tall Tree and the Eye* sculpture. The use of digital form-finding techniques with gravity simulation, explicit-history tools, together with the study of sphere packing and curved-mirror reflections, allowed the development of a geometrical model that could adapt and change accordingly to the design and structural progress from the initial stage to the construction phase.

SYNOPSIS

The sculpture is the result of a collaboration between Arup and the artist Anish Kapoor, exhibited at London's Royal Academy of Arts in 2009 and at Bilbao's Guggenheim in 2010. It comprises 73 mirror-polished stainless steel spheres, stacked to a height of 14 metres, which creates the appearance of weightless floating bubbles rising into the sky. Each sphere has an average diameter of 1 metre and a wall thickness of just 1–2 mm – a fragility that presented one of the major challenges of the design process. For this reason the sculpture has required an inner structure of three carbonated steel masts, linked together by curved bracing elements and connected to a steel base frame at ground level. The hollow spheres have been fabricated with a high-pressure water technique and then were mirror-polished.

When approached by the artist with a concept of stacking several mirror spheres, the Arup AGU (Advanced Geometry Unit) team examined and developed multiple methods and design options.

SPHERICAL PACKING

A first approach was analysing spherical packing theory in order to achieve an ideal design that would:

· Avoid visibility of connections between the spheres.

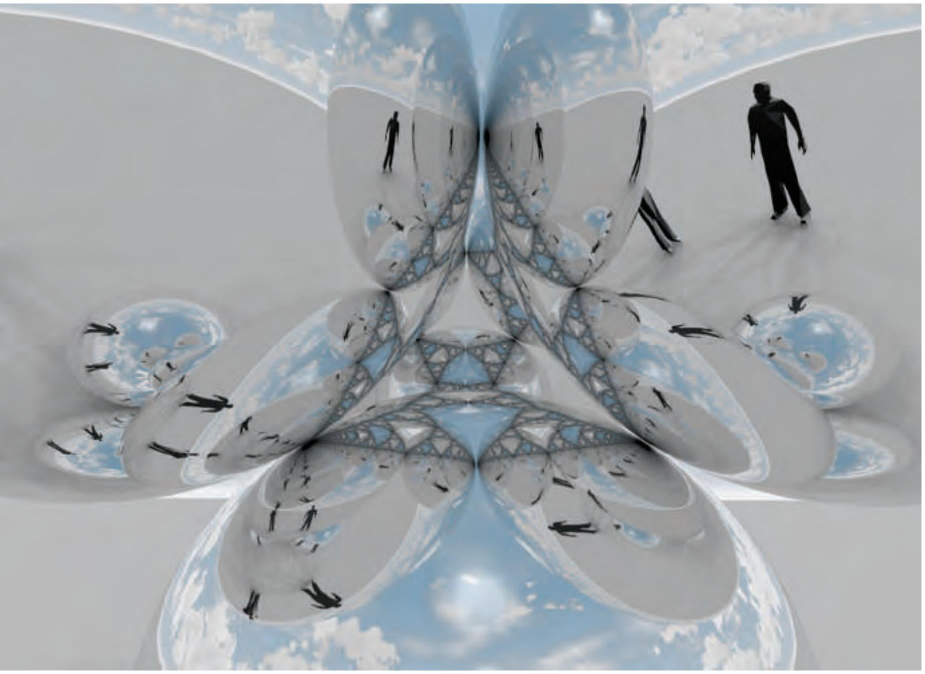
· Avoid visibility of any structural element.

· Present the minimum necessary quantity of structure.

· Be based on a simple construction sequence.

1: The *Tall Tree and the Eye* sculpture in the Royal Academy of Arts courtyard, London.

2–4: Sierpinski and Apollonian gasket, a tetrahedron of rendered spheres and a photograph of the sculpture.



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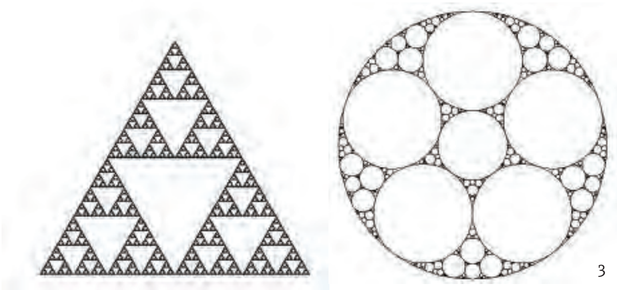

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As soon as the design process began, the focus was to find the most efficient way of packing spherical objects and whether there is a rule that facilitates constructing and controlling tangencies between numerous spheres. The regular packing system would provide modularity that facilitates the design process, constructability and the fabrication process. The two most efficient regular packing systems where the highest density arrangement (0.74) can be achieved are:

· The hexagonal close packing (HCP) = where the sphere's centres lie on the tetrahedron vertices'.

· And the face-centred cubic packing (FCC) = where the spheres centres are located on half-octahedron vertices.

For this reason placing the spheres centres on either an octahedral or tetrahedral packing configuration would establish an effective way of controlling tangencies between all spheres. But, at the same time, the regular packing system would give a far too regular arrangement strongly perceivable to the spectator. The irregular packing system, on the other hand, would provide the visual effect of a casual layout but would also require extra structural elements. This packing arrangement has been explored through the Reactor toolset in Autodesk 3ds Max, which enables simulation of complex physical scenes. The Havok's physics technology, used in Reactor, provides a dynamic environment for the objects in the scene (for example assigning gravity force or collision power between rigid bodies once created in the 3D space). The results of these investigations on both regular and irregular packing characterised the sculpture's final geometrical outline. It therefore combines the two systems, both for structural and aesthetical reasons.

REFLECTION ANALYSIS

Studies on the reflection properties of mirror spheres were carried out to enhance the control of the visual impact that the sculpture would have on future

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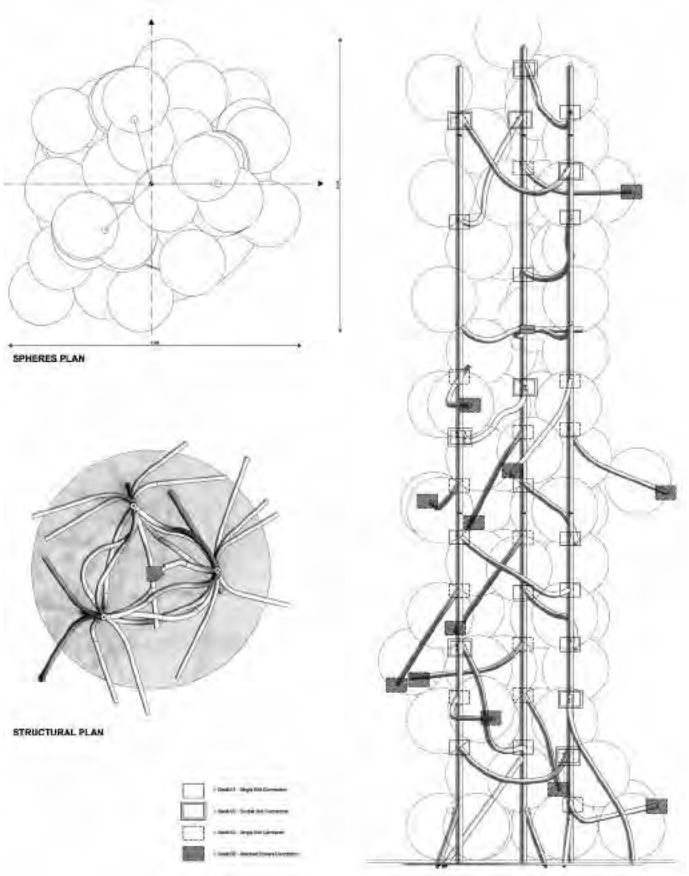

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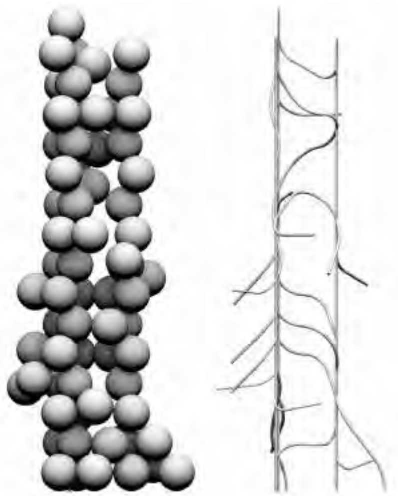
5–6: Although every single sphere weighs approximately 45kg, the result of the design process has been a stable and yet light structure appearing to be almost weightless.
This effect has been achieved by means of an inner structure of three carbonated steel masts linked together by curved bracing elements and connected to a steel base frame at ground.

7: *The Tall Tree and the Eye* arrives on site. The protective layer is peeled away, the first reflections appear.



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observers. Once basic convex mirror properties were explored, several 3D computer models were then developed in order to visualise the effect of reflection on multiple mirror-tangent spheres. Photo-realistic renderings provided images that were then verified on-site as very close to reality. Issues such as how reflection is affected by the observer, how angles and distances between spheres affect the reflection or how the context will be distorted in the reflection, were the starting point for further considerations. For example, different angles, relative positions and diameters between several spheres can affect the result of the reflection. Far more interesting reflections can also be achieved when the spheres centres lie on a plane non-orthogonal to the viewer. Furthermore, an opening at the lower level of the sculpture was designed in order to allow the visitor to enter the sculpture and gaze up at the endless reflections as if into infinity.

HYPERBOLIC GEOMETRY

The research for the underlying principles behind mirrored reflection on multiple spheres led to the study of transformations in 2D space (such as inversions) and in the hyperbolic plane (such as Möbius transformation). They explain, at best, the effect of reflection on the spherical mirror surfaces. What happens in 2D inversion with respect to a circle, occurs in the 3D space with a set of tangent spheres under inversion to each sphere. For this reason the multiple-tangent spheres of equal diameter will produce a fractal reflection as shown in the computer-rendered image as well in the photograph of the sculpture in figures 2–4. This fractal pattern would then become increasingly complex and rich when people and surrounding buildings are introduced into the space and when packing is carried out in an irregular form.

THE DIALOGUE BETWEEN STRUCTURE & GEOMETRY

The form-finding process of the conceptual design had to integrate aesthetic requirements together with geometric and structural ones. If a 3D layout succeeded aesthetically it would then be exported into a structural analysis software (Oasys GSA Analysis) to verify the local and global stability of the sculpture. These results would then be used as feedback for further changes to the 3D model that, in a back-and-forth process, would generate further considerations.

SPHERE TYPES

To provide an insight into the geometrical attributes of the *Tall Tree and the Eye* sculpture a classification of the spheres is necessary. They are all characterised by a different number of tangencies with each other and by the type of structure contained within:

· The mast spheres are the spheres that conceal the three carbonated steel masts and have at least two points of tangency with other spheres.

· The inner-bracing spheres are the spheres that enclose the curved-bracing structure (linked to the three masts) and have at least three points of tangency.

· The cantilever spheres are the spheres that will be supported by a curved cantilever structure connected to just one mast.

· The top-mast spheres are three extra mast spheres that have been inserted on site on the summit of the masts.

· The ground spheres are particular spheres that have been added at ground level for improved stability and enhanced reflections.

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Several geometrical constraints had to be established in order to fulfill visual and structural requirements. The first priority was to avoid visibility of the inner structure throughout the sculpture. This explains why all spheres listed above had to be tangent to either one, two, three or four others. What's more, the diameter of the three masts had to be as small as possible. The three masts had to be located at an equal distance from the global point of origin, not exceeding 1 metre, so as to enable tangencies between the mast and the inner-bracing spheres. Multiple alternatives for inserting and connecting the spheres on the structure were provided, always bearing in mind the geometrical constraints. It has then been a crucial task selecting which mast spheres would be connected to the inner-bracing spheres, because their location would determine the position and shape of the curved structural bracing and therefore the structural performance of the entire sculpture.

PARAMETERS

It was necessary to assign parameters that could completely define the sculpture's geometry and would enable control of any changes required in an efficient way. Once defined, a 3D model that could adapt and change quickly, according to the design and structural progress, could be achieved either through implicit or explicit history tools that are tightly integrated with Rhino's 3D modelling tool. The best solution for this project has been provided by the explicit history tool Grasshopper (a graphical algorithm editor) where parameters could be assigned and linked through several components. The best characteristic of this tool has been the fact that, in contrast to the implicit history tools, it could provide an immediate visual feedback and full control of each single component and stage of the process created by the user.

Whenever one of the parameters changes, the whole model consequently adjusts to suit the initial requirements. In this way any geometrical variation required either for aesthetic or structural reasons could be rapidly exported into analysis models for structural tests. Finally, once the geometrical model was built and finalised, the polar coordinates of each single sphere was exported into a spreadsheet in order to enable the fabricator to control and rebuild the 3D model with any software.

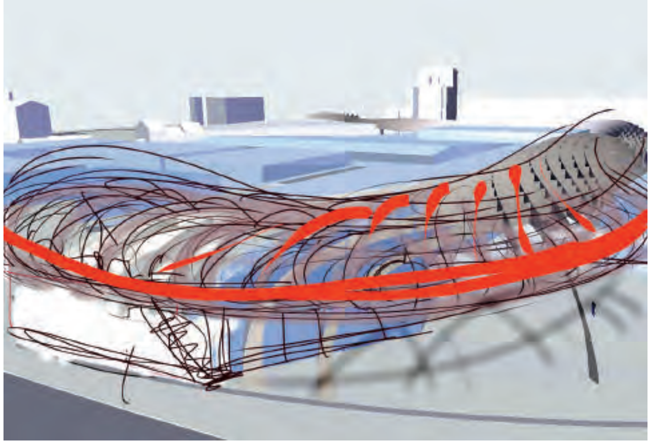
The process taken to create this soaring installation combining art, geometry, architecture and engineering, demonstrates a novel computational approach to exploring, modifying and exchanging design information between artist, architect, engineer and fabricator.

MÉDIACITÉ

PAUL MADDEN & GEOFF CROWTHER,
RON ARAD ARCHITECTS

Ron Arad Architects (RAA) were invited to design the new mall, roof and public spaces of the 40,000-square-metre mixed-use development known as Médiacité. Situated in Liege, once the world's foremost centre for steel production and since in economic decline, the building stands out as a symbol of the city's regeneration. The 350-metre-long mall weaves through the fabric of the refurbished old market centre at one end, through the new two-storey building to connect through to the new Belgian national television centre at the other. The design of the roof unites these elements with a complex network of steel roof ribs that undulate through the mall. The lattice of steel sculpts the volume of the mall beneath, varying both in height and structural depth, to form a variety of different spatial experiences. As the structure exits the volume of the main buildings (at the two piazzas and at the link between the old market and new building) the steel ribs wrap downwards, merging into the facade and forming the building's envelope. The structure is entirely free-spanning along its length and width, with 200-mm-wide steel ribs that vary in depth from 300–1200mm, crossing through each other in a deformed grid-like network. To minimise loadings, the complex 3D structure is clad in transparent lightweight ETFE – pneumatic Texlon cushions that allow light to penetrate the roof while moulding themselves to the irregular structure. As the roof gradually transforms into facade, the ETFE cladding merges into curved aluminium rain-screen panels and glazing.

The architects were brought onto the project after construction on-site had already begun. Asked to completely rethink the design for the mall but working within site constraints already in place, they entered a highly accelerated programme, which required the design, engineering, fabrication and installation of the project within 34 months. They chose to work with steel not only for its close connection with Liege but also for the speed and accuracy with which it can be fabricated, and the freedom it gives to develop something geometrically unique. The normal design process at Ron Arad Architects (RAA) leads very quickly to 3D modelling. It's the same approach used to develop a bespoke chair or mass-produced industrial design object. The architects don't use any traditional architectural software in the early stages, starting instead with Maya



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1: Fall arrest netting placed over 25 metres of spanning roof section, allowing specialist contractors to 'walk on the air', prior to ETFE installation.

2: Digital sketch of RTBF Piazza using a touchscreen monitor, over work-in-progress Maya 3D model screenshot. This technique allows for rapid development of the 3D model while maintaining an exploratory sketching process.

3: Curved cantilevered concrete slab edges, to take the outriggers of LIII Part 1, the largest spanning roof section.

4: Temporary propping of the 70 metre long LIII part 1 section of roof during installation. This is done prior to any final on-site welding and before the structure becomes active.

and utilising its powerful history tools (combined with NURBS), allowing them to sketch and edit freely in 3D. The architects also use a touchscreen and pen, directly into the model screen. The interweaving of the editability of Maya, combined with the architects' sketching, creates a flowing iterative design approach that is a hybrid of two distinct working methods. This encourages them to not become too fixated with tool sets or particular 3D methodologies, by retaining an exploratory sketching process while overlaying the rigour of testing real world physical properties.

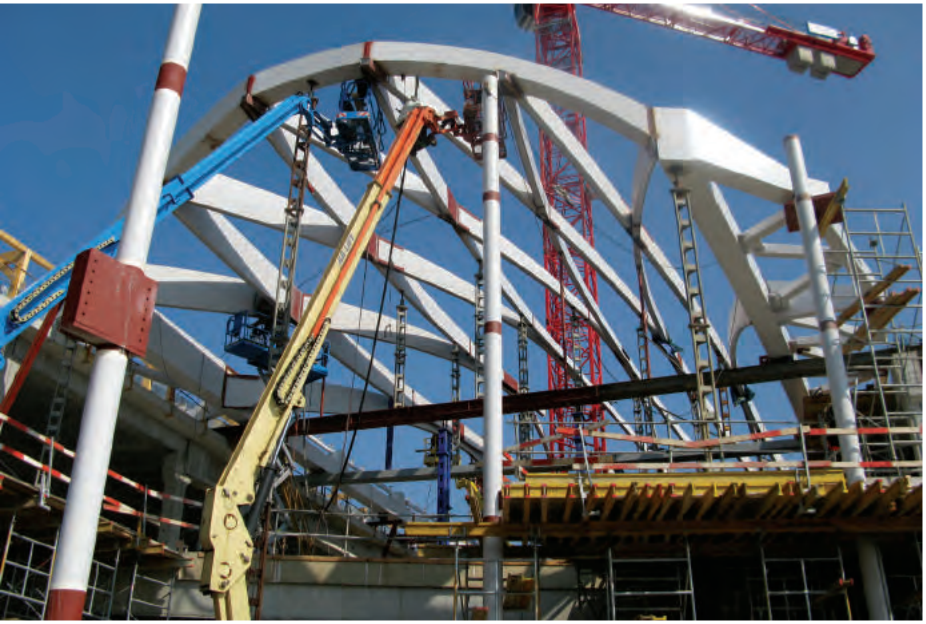
At some point, depending on the type of project, Maya's usefulness can start to slow down; especially when higher levels of dimensional control are required. Also, with a project like Médiacité, where the architecture and structure are indistinct from one another, translation ease and accuracy become paramount. During the early stages there were discussions between the engineers and the architects about how best to take this forward and it was agreed that several approaches needed to be explored. Buro Happold, like many large practices these days, has a specialist geometry unit. As the architects use Microstation for 2D drawings, Generative Components (GC) was considered as an ideal solution to achieve a seamless parametric integration. Unfortunately this proved to be too complex and it also meant that the engineers would drive the form finding and control the final architectural form of the steelwork rather than the architects.

There were several key forces that both changed the project and created a route forward. In the original concept design, the density of the lattice was much higher and almost all of the ribs were double-curved. This was clearly not cost-effective due to the additional steel weight and fabrication time. The architects embarked on a process of optimisation to reduce the amount of ribs and to look for areas where it would be possible to make ribs single-curved, without detrimentally affecting the overall design. Also the roof, at 350 metres in length, was always envisaged as a single, continuous entity. However, due to the fact that the mall would be a primary escape route, compartmentation became an additional parameter in the design. As a result the roof had to be broken down into eight sections, dictated by maximum smoke compartment sizes and the need for retractable smoke curtains between each section. This meant breaking the roof geometry into discreet components, which made the development more manageable and also set up a strategy for phased fabrication and installation.

Controlling these complex interfaces at fabrication tolerances created enormous data sets, which weren't really manageable in the 3D programs the architects used, resulting in the need to turn to industrial design software to create the parametric and dimensionally precise model. The architects used Alias Studio for particularly difficult sections of the roof, where dimensional control, combined with G1 geometric continuity was necessary to integrate glazing and other facade elements. This route meant they could control the geometry as they wanted but it also meant that there was more pressure on the architects to integrate findings by the consultants and subcontractors. Effectively there was a feedback loop, with the architects at the nexus, continuously returning to the original model to make complex updates and then releasing them to filter down the chain. This was a direct result of the fact that the geometry of the roof had to meet localised criteria at critical points. However, with such an integrated design, these small changes had the potential to send ripples through the global geometry and create problems in other areas.

Regardless of the initial difficulties of workflow between the architects and engineers, programmatic pressures meant that the key to the success of the project would be to extend this design loop into the fabrication process, since major design issues were being resolved days before fabrication and installation. The primary focus was to use digital technology to allow efficient iteration. Every rib is unique and, in order to keep the project economical, the fabrication process needed to be numerically controlled and robotically produced as much as possible. It became apparent that the steel fabricators' software was only able to import coordinate information; no direct geometry or other architects data was possible. The engineers' smart geometry unit researched into scripting for a solution and developed a script for breaking the curves down into nodal coordinate points of varying density, depending on the rate of curvature.

The workflow path started from the architects' finalised model information being converted to a set of simple centreline NURBS curves. The engineers then reduced the curve model to a set of coordinate points via their customised script. This set of points was issued to the fabricators as a linked data spread-sheet, along with the architects' final rib centreline model. After everything, the complex 3D roof design was reduced to nothing more than an Excel document. The fabricators took this information and regenerated the architects' model as a fully realised construction model, containing every single piece of steel, right down to internal stiffener plates and mechanical fixing details. This model then completed its journey by returning to the architects and engineers for analysis. This process cycled through multiple iterations per roof section until all problems were solved. At this stage all other specialist fabricators would use the final fabrication model for the development of other elements that were defined by the steelwork, namely cladding, glazing and, in particular, the ETFE cushions on the roof. The final analysis was undertaken only after the ETFE 'T'-saddle fixing nodes were in place in the model, as they could be fabricated simultaneously with the main roof ribs in the factory, to reduce on-site time.



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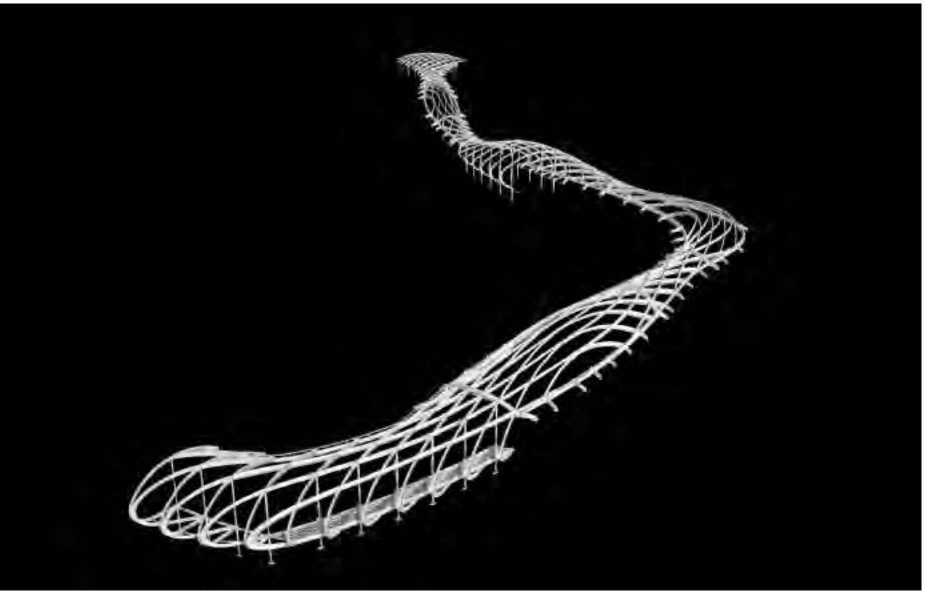

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5: Final fabrication model. The full extent of Médiacité at 350 metres long, split into eight roof sections. The model contains every detail and every single piece of steel installed, including internal stiffeners, movement joints and mechanical fixing details.

6: Roof sections were assembled in a large hanger prior to site installation. This allowed the architects, engineers and fabricators to check tolerances and details.

7: Four sections of roof installed and at different stages of completion. LII Part 2 (in the distance), during ETFE installation and LIII Part 3 (in the foreground), the most highly curved section of roof prior to structural activation.

8: RTBF Piazza after installation of cladding, glazing and ETFE.

The analysis included a clash check between all fabricator model components and the architects' final model. This in itself created issues, because there was no way to automate the process, resulting in the need to 'physically' inspect the 3D model geometry millimetre by millimetre, checking every curve and rib intersection, movement joint and ETFE 'T'-saddle orientation by eye.

After the fabricator's final 3D model was approved, all the complex 3D curved ribs were broken down into their constituent parts of webs, flanges, stiffeners, etc. and converted to developed surfaces. Like pattern-cutting in tailoring, the uniquely shaped plates were CNC plasma-cut and individually numbered. Following this, CNC jig software generated the heights and setting-out distances of the individual jig components. The plates were then draped over the modifiable jig to form the correct curvature and the welding process could begin. In addition, it was envisaged that, where possible, a robotic welding system would be utilised. However, the welding system at the time was only able to weld in two axes. As a large proportion of the ribs curve in three axes, most of the welding had to be done by hand, lengthening the process of final fabrication and creating thermal deformation in the steel, which then

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needed to be corrected. Furthermore, some of the more highly curved plates needed to be rolled, using an almost artisanal technique of hand-rolling through a huge plate bending machine and individually checked and measured by tape and eye. This combined method of using both the highly digital and the handcrafted, embodies the conceptual methodology of the architect's studio. It's an indictment to the necessity of moving between these two conditions for the benefit of the project, rather than sticking tenaciously to one or the other, as representative of a specific ideology. Finally, pre-assembly of entire roof sections was carried out in large hangars, to check fit and accuracy. This was an opportunity for the architects and engineers to do a final analysis at 1:1. Depending on the geometry of the specific roof section, components were pre-welded into ladder arrangements during pre-installation, therefore reducing the need for on-site welding.

As a practice RAA are not currently exploring generative or associative design through software. Instead their interest lies in pushing the relationship of material technologies and geometry (as can be seen in the practice's industrial design work). The dilemma of when to jump from one program, that has fluidity and freedom to sketch and edit in 3D, to another, which has precision and dimensional accuracy, is always a problem. Only when the geometry of a project is fixed would the architects normally translate it and remake it with higher accuracy. However, the geometry of Médiacité needed to be constantly edited, even during fabrication, demanding a more complex workflow. Despite the streamlined efficiency of the digital design process, the final physical form is still, for the most part, reliant on traditional handcrafted techniques. Robotic automation, common in industrialised manufacturing, has yet to find its way successfully into large-scale architectural works and, at present, there seems to be little that architects can do to improve this without limitation. For the Médiacité project specifically, the main problems were a result of software. If the right software existed the architects could have facilitated a smoother process towards fabrication, by translating the model information into a more accurate but still editable geometric entity that could be shared across the entire life of the project. This wasn't possible and it held back discoveries that would have increased the quality of the final result.

WAVED WOODEN WALL

HANNO STEHLING & FABIAN SCHEURER,
DESIGNTOPRODUCTION

The Kilden Performing Arts Centre in Kristiansand, Norway, designed by Finnish architects, ALA, will provide facilities for the Kristiansand Symphony Orchestra, Norwegian Opera South, and a number of local theatre groups. It is currently under construction and is expected to open to the public in 2012.

The outstanding design feature of the building is the so-called 'Wave Wall', a 10- metre-wide and 22-metre-high overhanging and undulating timber wall that looms over the foyer areas and defines the building's facade by the waterfront. The wall cantilevers up to 35 metres and is bisected by a vertical steel/glass facade into both interior and exterior parts.

designtoproduction joined the project as a subcontractor of Trebyggeriet, the timber constructor commissioned to implement the facade. Together with structural engineers SJB.Kempter.Fitze and, timber fabricators, Blumer-Lehmann, a construction concept was developed, dividing the whole facade into 126 elements that could be prefabricated to minimize on-site labour while also guaranteeing a high level of precision.

A row of 22 differently inclined I-profiles act as an interface to the main building structure. Each facade element consists of two straight primary beams connecting it back to the steel structure, typically 9-11 single-curved secondary crossbeams and up to 180 straight but twisted oak cladding boards.

The curtain-like geometry of the Wave Wall was to be defined by a ruled surface between a straight upper and a curved lower edge. However, this surface had to meet specific needs. To keep the boards' middle axes straight (so they would only twist following the changing surface direction but could still be produced from straight laths), they had to run along the surface's generatrices. In order to align the cladding boards with the lateral element borders nicely, they had to be parallel to the steel girders in XY-projection. To fulfill both requirements, a ruled surface with all generatrices having parallel XY-projections was generated and accepted by the architects. The whole facade was implemented as a parametric model in McNeel's CAD-System Rhinoceros, using RhinoScript boosted by extensions written in Microsoft.NET.

1: Facade under construction. 305 primary and 1,769 secondary beams with 12,248 oak cladding boards.

2–3: Facade elements being lifted into place, and a package of facade beams ready for transportation to Norway. All secondary beams feature 'seat cuts' for precise placement.

4: Structural model of the facade.

5: One of the 1,500 drawings automatically generated from the CAD model. The corner element shown here features a double-curved beam as well as a ventilation opening.

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The parametric system consisted of nine different components (two kinds of main beams, six kinds of secondary beams and the cladding boards) with specific detailing as well as nine different connection details.

The most complex and versatile components were the secondary beams. While positions and cross-sections of the primary beams were largely defined by the geometric surroundings (i.e. positions and inclinations of the steel girders, distance to the reference surface), the secondary beams were formed by aspects of the facade system itself. Specifically, they had to follow the highly curved reference surface while also upholding the oak cladding boards and withstanding frontal and lateral wind loads. To determine and verify their positions and cross-sections, an iterative workflow with the structural engineers was set up. To make the geometry compatible with the structural analysis software, the curved beams had to be emulated by rows of short, straight beams, balancing geometric deviation with a workable number of entities in the structural model. The process of exporting, validating and applying changes, and exporting again, was executed several times until a satisfactory configuration was found.

The next optimisation step was on behalf of the timber fabricator. Depending on cross-sections and bending radii, the beams had to be milled out of straight or individually produced curved glue-laminated timber blanks. At extreme curvatures, parts even had to be made out of cross-laminated plates. Weighing material cut off against timber blank diversity, it was possible to mill up to ten different curved beams from identical blanks without exceeding acceptable cutting angles for timber fibres.

To make assembly as fail-safe as possible and allow for a very high level of precision, nearly all positions at component connections were marked by slots and similar details that were included in the parametric model. To ensure the desired continuous gap pattern along the facade, the secondary beams were enriched with 'seat cuts' for every cladding board. Thus a good portion of assembly complexity was directly embedded into the parts.

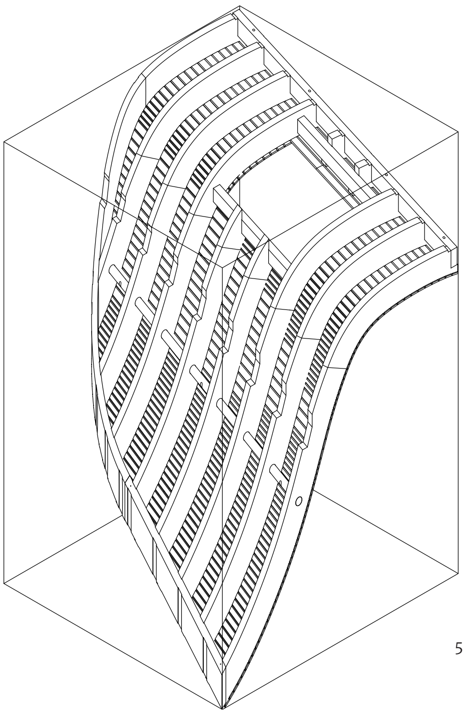
Production data for both blanks and final pieces was exported directly from the parametric model. Depending on the type of component, 3D models of different kinds were produced. For the oak cladding boards, machine code was directly generated, as their relatively straightforward geometry allowed for this, while their sheer number made the additional effort worthwhile.

Furthermore, the system included automatic plan generation, including dimensions, reference point coordinates, parts lists and volume/weight calculations. PDF plans were produced of each element in its assembly orientation (laid out 'as flat as possible') as well as in its final installation position. All components were labelled to help assemble more than 180 similar oak boards per element.

Production of the different parts was split amongst consultants according to their specialised capability. All curved secondary beams were produced by Blumer-Lehmann in Switzerland and shipped to Norway, while primary beams and cladding boards were done by Trebyggeriet and Risør Trebåtbyggeri, a boat-building company that also executed the assembly. The assembled elements were then shipped to the site just in time for installation.

As of the end of 2010, a bigger part of the facade has been erected. First pictures seem to justify the prefabrication concept and its acceptance of rather complicated CNC-fabricated parts for the sake of preciseness.

Extensive constructive systems in non-repeating geometries are practically impossible to implement without the help of parametric modelling, as they bear thousands of geometrically unique details that can only be handled when abstracting them into a considerably smaller set of rules. Still, applying parametrics is no black-and-white decision; the extent to which this is driven can vary greatly.



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Full-blown parametric modelling systems like Bentley's Generative Components or McNeel's Grasshopper are able to produce immensely consistent models, but bind the designer to parametrics for good. Even the most extreme and exceptional entities have to be covered by the parametric rules or they cannot be part of the parametric workflow at all, which in turn devalues the advantage in terms of consistency and fail-safety. In our experience there is a limit on the flexibility parametric systems offer, above which they tend to add more complexity than they resolve.

The Kilden facade was carried out in a more step-by-step approach. Each automated procedure resulted in (virtually) tangible geometry that could be validated and punctually adjusted before continuing. The system would flag possible problems or failures, letting the designer decide whether time should be taken to broaden the scope of the algorithm and repeat the step or resolve them manually.

As a consequence, the automated procedures did not care about the history of their input geometry. Thus, it was possible to manually create or adjust rare details that occurred only once or twice in the whole facade without foregoing the ability to incorporate the results into subsequent automated processes.

So the parametric system practically consisted of a set of highly specialised tools that, if applied one after another, would cover the complete workflow from input geometry to fabrication data, but could also be adjusted or even substituted individually without affecting the functionality of the system as a whole. Because most intermediate states were preserved as geometric entities in the model, it was even possible to roll back a few steps and start over in single parts of the facade, leaving the rest untouched, a capability that turned out to be very important due to the concurrency of modelling, detail refinement and actual building.

Admittedly, such a 'semi-automated' workflow puts the responsibility for model consistency back into the designer's hands. But, if carried out accurately, it is a very powerful method to incorporate exceptions into otherwise rigid systems, offering an adequate balance between the labour-saving and error-reducing efficiency of parametric design and the flexibility and pragmatism necessary for larger real-world projects.

RADIOLARIA PAVILION

ANDREA MORGANTE,
SHIRO STUDIO

In late 2008 D-Shape successfully developed the first 3D mega-printer to allow the seamless and free-form construction of monolithic structures on a large scale. Radiolaria represents a micro-architectural experiment developed by Andrea Morgante of Shiro Studio as a commission for and in association with D-Shape. The Radiolaria pavilion aimed to define a complex, self-supporting structure that could demonstrate and test this pioneering construction technique. Measuring 3 x 3 x 3 metres, the structure represents a scale model of the final pavilion (Radiolaria XL), due to be built in late 2010 in Pontedera, Italy; and will be 9 metres high.

CONCEPT

The aim of Radiolaria was to produce a geometry that could be self-supporting and demonstrate the capabilities of this innovative technology. Its geometrical morphology reflects the potential provided by the mega-printer, capable of building highly complex forms without the use of provisional, temporary formwork or disposable, expensive moulds. Made of artificial sandstone without any internal steel reinforcement, the pavilion's design and execution had to be intrinsically resilient to several static stresses. Ernst Haeckels' studies on radiolarian structures and comparative anatomy has been an invaluable source of inspiration: mineral and siliceous skeletons, through a gentle evolutionary formation process, share an affinity with the way that the mega-printer operates, through the gentle, slow deposition of mineral and siliceous material, layer after layer.

MATERIAL

D-Shape's mega-printer utilises an inorganic binder with sand or mineral dust, which has been subjected to traction, compression and bending tests. Binder transforms this sand or mineral dust into a stone-like material (i.e. it has micro-crystalline characteristics) with a resistance and traction superior to Portland cement. Calcium Magnesium Carbonate, $CaMg(CO_3)_2$, was used for the fabrication of Radiolaria as the main aggregate. This was the material available at the time and it was sourced just a few kilometers away from the workshop. The ability to use sand as the predominant building component connects the printing process to natural resources.

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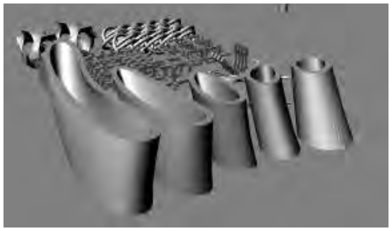

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1: Radiolaria completed (detail), 2009.

2: Printer bed awaiting first layer.

3: Radiolaria XL: volumetrical layout optimisation – leg sub-parts. Screen capture of the printing command, showing additional objects that will be printed. 2009.

4: Printing completed: sand removal.

5: Early reference images – radiolarian structures. These mineral skeletons have provided an inspiring view over light and rigid 3D structures, 2009.

6: Printing completed: retaining walls are removed. This material, once crushed and pulverised again, could be recycled for new structures.

Even the colouration and appearance of the printed structure will vary and inevitably show the use of the local sand or mineral dust.

TECHNOLOGY

The external lattice structure holds the printer head, which represents the real core of this new technology. The process begins from the design file, which is converted into STL format and imported into the software that controls D-Shape's printer head. The printing of each section takes place in a continuous work session: during printing 'structural ink' is deposited by the printer's nozzles on the sand. The solidification process takes 24 hours to complete. The printing starts from the bottom of the construction and rises up in sections of 5–10 mm each: upon contact the solidification process starts and a new layer is added. Surplus sand that has not been embedded within the structure acts as a buttressing support while the solidification process takes place. This surplus sand then can be reused on future prints.

PRINTING RADIOLARIA

The original digital model was developed in four weeks. Several softwares were tested and in the end a Sub-Division modelling software was chosen to define the final geometry. The file, exported as IGS, was then emailed from London to the D-Shape workshop in Italy where the printing process commenced two days later. The digital file was automatically divided in layers by the printer's specific software that controls the printing nozzles; each layer was set to 10-mm thickness. The printer resolution was defined not only by the layer's thickness but also by the number and density of voxels (3D pixels). Each voxel represents a single drop of 'ink' that the machine's nozzle will leave on the sand bed. Each voxel measures 5 x 5 x 5 mm. The machine printed with very few interruptions, with a printing speed of 150–200 mm per day. The whole printing process for Radiolaria took just over a week. The gross weight is approximately 500 kg: 300 kg for Radiolaria and 200 kg for the waffle base, necessary for bracing the base of the structure.

During printing the software automatically adds sacrificial retaining walls; these walls hold the sand that is used during the printing process. Once the printed structure was cured and solidified they were destroyed and the radiolarian emerged from the unused sand. Once unveiled it was evident that the surface was not as entirely smooth as planned. This was due to the different calibrations of each single nozzle. It was necessary, therefore, to manually

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eliminate these irregularities. Nevertheless, Radiolaria shows that a monolithic free-form self-supporting structure can be printed directly from a digital file without the use of any provisional formwork.

Following the printing of Radiolaria operations begun for the printing of Radiolaria XL (a 9-metre-tall version that will be positioned outdoors and will welcome visitors to the town of Pontedera). Radiolaria XL sets a new level of challenges due to its sheer scale. In order to be transported on-site Radiolaria XL is being printed in several pieces. Some are already visible. In order to create a lighter and yet rigid structure these pieces are hollow, somewhat resembling bone.

CONCLUSIONS

Developing Radiolaria, from the very initial concept to printing, has been a unique challenge; nothing similar ever has been tested before, placing considerable pressure on the design and the fabrication process. The ultimate challenge was inevitably to demonstrate not only the complete symbiosis between language and process but also the full independency of the process. By independency I mean the lack of post-process actions and additions (material and processes) to achieve the final design. Radiolaria wanted to demonstrate the shortest route from the generation of a digital file to the completion of the design. This perhaps was the strongest challenge faced by the team. Retrospectively the submission of the 3D data file to the printing machine and the printing of a fully structural design in real scale, with no other intermediate actions, made the designer aware of the full potential of this process and how much more can be achieved in this direction.

The fabrication of Radiolaria was only possible thanks to Enrico Dini, founder of D-Shape, who has passionately supported Shiro Studio throughout the entire design process. There was no external financial contribution or sponsorship during the concept development and the fabrication process: the design and fabrication team decided to invest their own resources to explore this new construction process and demonstrate through a ‘small’ piece the much greater possibilities lying ahead in the field of digital fabrication.

LOUVRE ABU DHABI
1:33 LIGHT-TEST PROTOTYPE

BENJAMIN S KOREN,
1:ONE COMPUTATIONAL GEOMETRY

The Louvre Abu Dhabi, to be completed in 2013, will be part of the world's largest concentration of cultural institutions within the Saadiyat Island Cultural District in Abu Dhabi. It will be the first universal museum in the Arab world and will showcase fine arts, decorative arts and archaeological artefacts, featuring the artistic achievements of different cultures that will be collected from all over the world.

Jean Nouvel's design of the project envisions an enormous dome, approximately 180 metres in diameter. It will feature a multi-layered skin, filtering the blistering desert sun from above, with the intention of controlling the microclimate near the gallery buildings below. As a result, bundles of skillfully orchestrated light-rays will emerge, a dynamic effect the architect termed his 'rain of light'. This aspect of the project was considered to be of such importance that, during the course of design, a large-scale prototype of the project was constructed, to simulate and ultimately verify this design intent. The specifications for such a model naturally surpassed those required in typical architectural models, as three simple facts and their associated challenges will reveal.

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1–2: Welding the dome's edge.

3: Partially clad structure, view from underneath the prototype.

4: Fully assembled structure.

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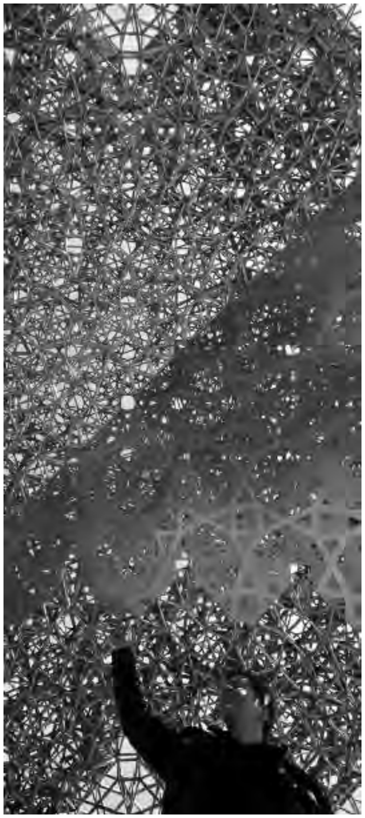

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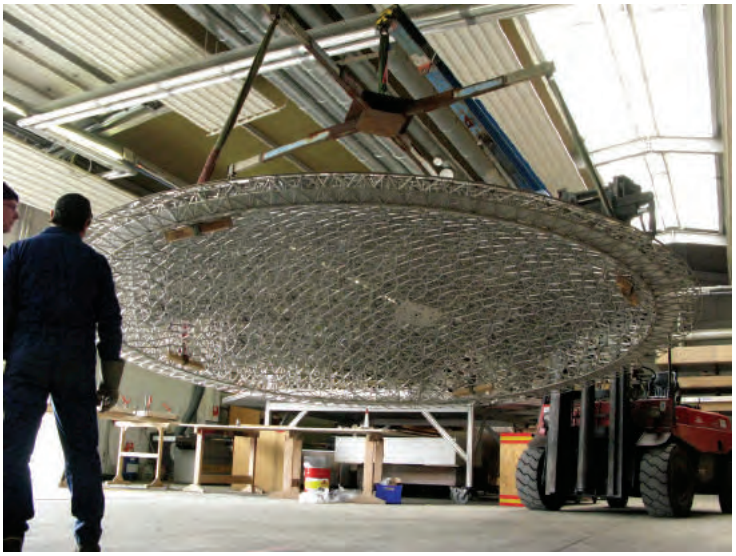

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1. At a scale of 1:33, the prototype measures 5.50 metres in diameter, posing a challenge for handling and transportation.

2. It consists of approximately 16,000 individual precision components in order to simulate the impact of the elements' geometry on the light conditions truthfully, posing a challenge to the methods of computation employed to generate the data.

3. It had to be erected on location in Abu Dhabi within a period of less than six months for testing under actual light and climatic conditions. Thus, the model itself had to be designed to withstand large temperature differences, posing a challenge in terms of assembly logistics and time schedule, as well as limiting the choice and mix of materials.

Broad challenges in the model's fabrication can be generalised into two sub-fields: those pertaining to the structure and those to the cladding.

STRUCTURE

The structure's geometry, developed by the architects and engineers, consists of a space frame with top and lower chords lying on spherical surfaces. The building engineers working with Nouvel have rationalised the structure to the point where, integrating the four resting points of the dome, it exhibits dihedral 4 symmetry. Thus, for the development of strategies on detailing, fabrication and generation of the structure, a focus on one of the dome's quarters was sufficient. Within each quarter, however, and as a result of the distortion of the structure's grid caused by the curvature of the underlying double-curved surface, the components are unique throughout. With approximately 2,500 unique structural elements per quarter, custom-fabrication of each component would still be a daunting task.

Further to issues of geometric definition, matters of statics had to be accounted for as well. Due to the outward thrust of the dome, two detailing methods were pursued in the structure of the prototype: the interior part consisting of separate elements, mechanically pinned together, while the edge was welded out of stainless-steel tubes, forming a tension ring along the perimeter. Basic structural analysis verified the structural behaviour of this strategy, ultimately resulting in a system that is over-dimensioned. The ultimate detail serving the computational generation of the pinned structure was a combination of stainless-steel nodes, laser-cut out of flat metal sheets, and CNC-turned solid aluminium bars.

The initial digital step thus taken was the high-precision, automated generation of the detailed structure. In order to achieve the creation of the structure, a plug-in was developed in VB.NET for Rhinoceros 3D. The architects centre-line model of the dome was taken as input to create an associative data-structure, both bars and nodes parametrically defined as simple components (classes in object-oriented programming terms). Taking into account the physical properties of the elements, each component was custom-generated in place, in accordance with the local geometric conditions. Due to the aforementioned effects of distortion, the generated structure included close to no standard elements: each bar occurring only twice within each quarter, each node occurring only once, resulting in 1,250 different types of bars and 1,079 different types of nodes for a single quarter. Since such a large variety of non-standard elements proved to be an enormous challenge for the purpose of constructing the prototype, an optimisation algorithm had to be developed, to increase the number of standardised elements. Since non-standard nodes are much easier to manufacture than non-standard bars, the focus was set on reducing the number of bar types.

Reducing the number of bar types was accomplished by analysing the distribution of bar lengths, strategically defining the lengths of standard bars. Components of varying length within a set range were grouped together. Within each set, all its components were subsequently replaced by the shortest bar within the group. As a result of reducing the length of each local bar, the arm-lengths for adjoining nodes, being parametrically defined, would grow to compensate for the difference. The optimisation algorithm was integrated as a second step into the plug-in. As a result, 1,250 different bar types were reduced to 44 standard elements, greatly reducing the cost of production and simplifying the task of assembly.

CLADDING

The cladding of the dome consists of an overlay of five layers on top and five layers below the structure, comprising strips of varied width. The data for the cladding provided by the architects was a multitude of single quad-strips, lacking any detail for construction at the scale of the model. Searching for a repetitive pattern, raw tiles that could ideally be produced out of a standard format, the result was an element based on a truncated square tiling pattern. As the prototype had to withstand temperature differences of approximately 60–70°K during the testing phase in Abu Dhabi, the same material as the structures bars were ultimately used – spherically pressed aluminium sheets.

All geometric operations for the preparation of the cladding had to be carried out in a flat plane. For that reason, the 3D data provided by the architects had to be projected onto a plane. An orthographic projection could not be employed because the cladding for the model had to be separated into varying levels, due to the use of aluminium sheets with standard thicknesses and the merging of cladding layers. Projecting the cladding orthographically would have distorted the pattern of the cladding markedly. All operations that were developed for preparing the cladding, also as part of the Rhino plug-in, were based on gnomic projections, towards the centre of the sphere, the tangent plane defined by the XY world-construction plane.

As with the structure, the cladding modules were generated in 3D, automatically flattened and exported for cutting. The raw sheets for the cladding tiles were pressure-formed. As the formed aluminium has a tendency to spring back and rebound, it was difficult to achieve a plastic deformation in the aluminium sheets that would shape and hold the curvature of each module at the precise radius once the pressure was released, due to the very slight curvature of the surface of the cladding. For that reason, the press tool was milled to a substantially smaller radius, allowing the sheet to rebound to the radius aimed for. As there are no mathematical means available to anticipate the behaviour of the metal sheet accurately, it had to be determined empirically. Two trials were required, working closely with the metal workshop producing the sheets.

Once the raw modules were pressure-formed, each unique layer tile was individually water-cut. The three layers of each module were consequently glued together and pressed in-between two forms that were milled to the final radius, resulting in an even greater approximation of the ideal radius. The prepared cladding modules were then assembled onto the structure, covering its entire top and bottom area. Once the structure of the dome had been completed and fully clad, it was disassembled, transported in five parts to Abu Dhabi and reassembled on site.

CONCLUSION

The ultimate goal aimed for in the fabrication of the Louvre's light-test prototype was attained after a series of successful light-testing campaigns were conducted on location in Abu Dhabi. It not only confirmed the need of using advanced methods in computation and methods of fabrication in the rehearsed construction of the prototype, but also in the analogous, forthcoming full-scale dome erection – a task of even greater complexity.

LARGE, COMPLEX, PERFORATED ENCLOSURES IN EXTREME ENVIRONMENTS CONTROL OF STRUCTURAL & THERMODYNAMIC BEHAVIOUR, FROM MACRO- TO NANO-SCALE

AL FISHER & SALMAAN CRAIG,
BURO HAPPOLD

This article presents the development of a large perforated roof of the Louvre Abu Dhabi is currently under construction on Saadiyat Island on the Arabian Gulf Coast. The shallow, 180 metre diameter dome, supported at only four points around its perimeter, is constructed as a steel space-frame under a complex perforated multi-layer facade.

A multidisciplinary team, consisting of members from Buro Happold, Atelier Jean Nouvel and Gehry Technologies, collaborated on generating a virtual integrated parametric model of the dome. The model enabled the structural, environmental, architectural and fabrication requirements to be optimised. Stiffness and stress levels within the space-frame were controlled automatically, selecting only component cross-sections produced in bulk by the steel industry.

The cladding pattern and composition was also generated parametrically. It was varied locally across the dome surface so that the optimal balance between radiant heat, luminance and light 'dappling' could be found for different spaces under the dome.

These macro-level design issues were also influenced by phenomena and material properties that act on a much smaller scale. Calculations and on-site testing showed that very large amounts of dew would condense from the humid air when the dome was subject to radiative cooling under clear night skies. The radiant and tribologic properties of the cladding surface became important factors to consider in the control of condensation and the development of a cleaning and maintenance strategy. The thermodynamic studies uncover a unique opportunity for dew-harvesting in the desert marine environment – an opportunity best 'unlocked' with a multi-scale approach to architecture and fabrication.

MULTI-OBJECTIVE STRUCTURAL OPTIMISATION OF SPACE-FRAME

The complex engineering and architectural requirements called for a new approach to structural optimisation. A novel iterative approach was developed, based on Buro Happold's Smart Sizer software. Structural, fabrication and architectural constraints were embedded into this multi-phase approach.

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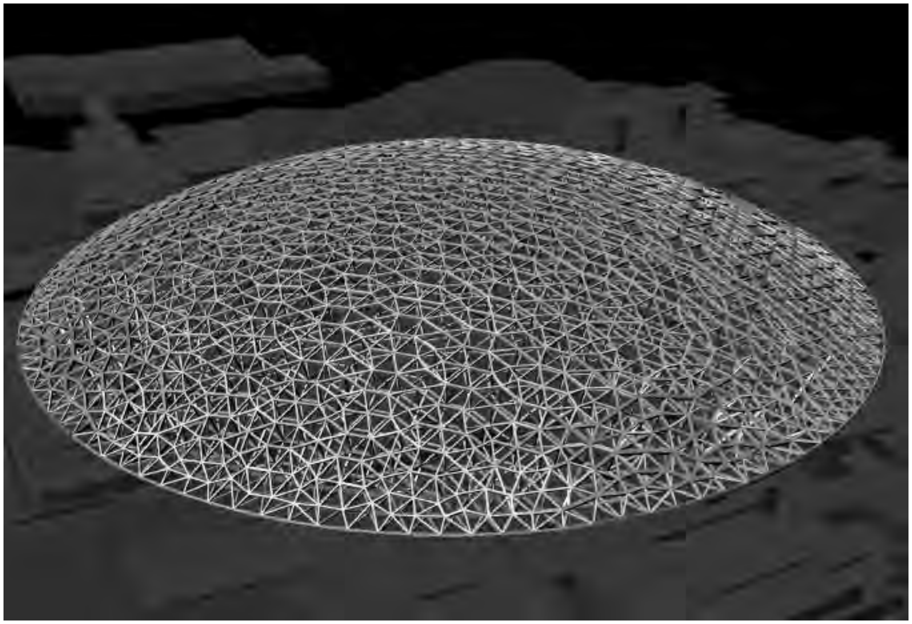
The procedure allowed compliance for multiple-load cases, while optimising for what was the dominant self-weight case. An initial deflection optimisation controls the stiffness distribution in the dome, enabling the designer to closely sculpt the global behaviour of the structure. Developed from virtual work methods (e.g. Baker[1]) local component sizes can be determined, based on the overall global stiffness requirements. This one -step approach was extended as a reiterative approach, accounting for the inherent redundancy in the structure. Following these stiffness requirements, a second phase of full limit state optimisation ensures all the specific local stress criteria are additionally satisfied. The image below right shows how, in utilising this automated approach, stiff regions within the dome naturally emerge, arching between the supports.

In addition, the final structural solution was achieved following a sensitivity analysis, optimising for a range of limiting deflections. This enabled a trade-off between the distribution of stiffness and thus the global structural behaviour of the dome and the minimum weight to be achieved.

The allowable steel component properties were selected from a list of standard section sizes, so no post-rationalisation was required when considering fabrication detailing. This design approach enabled a dramatic reduction in steel self-weight during conceptual and design development, however, an additional benefit of the tool was realised in the increased efficiency of the design process, allowing rapid exploration of numerous design options.

PARAMETRIC PATTERNING FOR DAYLIGHT & SOLAR CONTROL

Collaborating closely with project architects, Atelier Jean Nouvel and Gehry Technologies, the team developed a design methodology that enabled the precise cladding fabrication detailing to be controlled in a direct response to the engineering, environmental and lighting



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requirements; the result being performance-driven architecture. Working with Digital Projects (DP) as a central design and collaboration platform, a detailed model of the full space frame and multiple complex layers of cladding was generated. Defined fully parametrically this enabled not only flexibility and control in the design for experimentation and multiple design iterations, but also ensured exact and correct coordination between each component in the model.

To achieve the architectural intent of variable opacity across the dome a parametric cladding element was developed. Relationships were defined relating the widths of each opaque cladding element to the required translucency of the dome at that specific location, based on environmental simulations and various stages of calibration.

This adaptive cladding cell could then be mapped across the entire multiple dome surfaces, subtly responding to the varying translucency requirements as illustrated in figure 3. The two-fold optimisation process used to define the dome geometry for both structural and lighting performance illustrates how seemingly complex geometry can be achieved and in fact can also emerge naturally from the specific engineering requirements. Integrating into this design process standardisation and fabrication constraints means that the complex architectural aesthetic could be realised whilst meeting practical engineering limitations.

DEWFALL POWERED BY RADIATIVE COOLING: THERMODYNAMIC PREDICTIONS & EXPERIMENT

The clear sky above the Arab Peninsula lets escape a large, near-constant stream of energy, which is radiated from the Earth into outer space in the form of infrared electromagnetic waves invisible to the naked eye. At night, if the air is relatively still, this phenomenon called 'radiative cooling' will cause an exposed horizontal surface to cool several degrees below the local ambient temperature – enough, on humid nights, for it to reach the dew-point temperature and for condensation to form.

The greater the rate of radiative cooling, the greater the rate of dew production. Initial calculations suggested that, on humid winter nights, this effect could cause up to 60,000 litres of condensation to form across the 250,000 square metres of cladding that had an unobstructed view of the sky. In conjunction with the 2 grams of sea-salt settling each day on each square metre of exposed surface,[2] this high rate of dew-fall explains why the marine-desert environment is one of the most corrosive in the world.

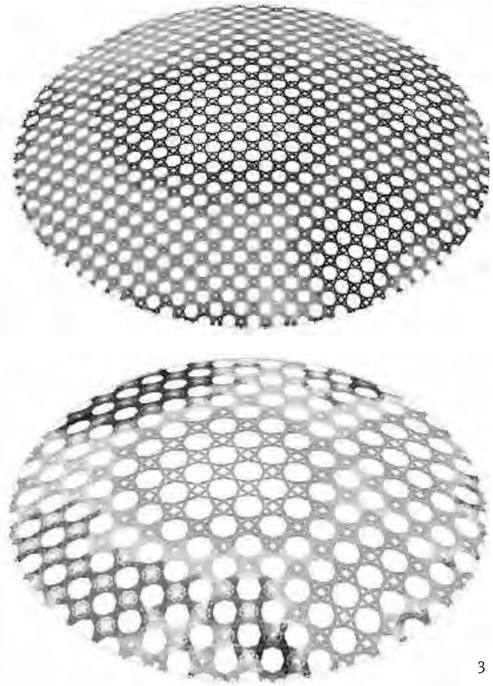
The material property that governs the rate of night-time radiative cooling – and, hence, the rate of dew-production – is emissivity. Emissivity is the proportion of radiant energy a surface will emit in comparison to an ideal blackbody. Both stainless steel and aluminium were candidates for selection in the design of the cladding. Anodised aluminium tends to be more emissive than stainless steels (though the type of finishing ultimately governs a material's emissivity). The production of dew in this case involves the interaction of radiant, latent and sensible heat that can be onerous to resolve. To avoid the need for iteration the Penman-Monteith equation was used.[3] This is an expression of the same heat balance, developed to describe evapo-transpiration or dew-fall on leaves.

Site testing was conducted over six days in order to validate the thermodynamic model. Moisture sensors were embedded into two stainless steel cladding panels, one of which was painted black so that measurements and predictions could be calibrated against results for a very high emissivity surface. In addition to the rate of dew-fall, panel surface temperature, ambient temperature, relative humidity, wind speed, infrared atmospheric radiation and solar radiation were also monitored.

Condensation formed on three of the six nights. On one of these nights the cause was not radiative cooling but the arrival of an early-morning sea-fog, that in the test location occurs, on average, 38 times a year.[4] The dewfall measurements were in good agreement with the thermodynamic calculations. The validated model was used to calculate monthly averages for dew-fall rates for a range of cladding materials.

MULTI-SCALE ARCHITECTURE FOR DEW-HARVESTING

How can this effect be taken advantage of in the future? Can large structures in this area of the world be designed



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so that this dew is harvested and put to good use? In order for this to happen, a number of technological and theoretical advances need to be applied in concert. The design challenge can be partitioned in terms of scale:

· Nano-scale. The goal is to produce dew and then have it roll away for efficient collection. This implies a super-hydrophobic surface with high emissivity. Advances in the study and replication of functional biomimetic surfaces – in particular self-cleaning surfaces, such as those inspired by the lotus leaf – are instructive here.[5]

· Micro-scale. Water condensed from the atmosphere is clean, but the collector surface will get dirty. How can the flows of water and particulate be separated? Perhaps a micro-surface architecture shaped like a river delta could transport the dew and deposit sediment at strategic locations. Constructal theory describes (and predicts) such architectures.[6]

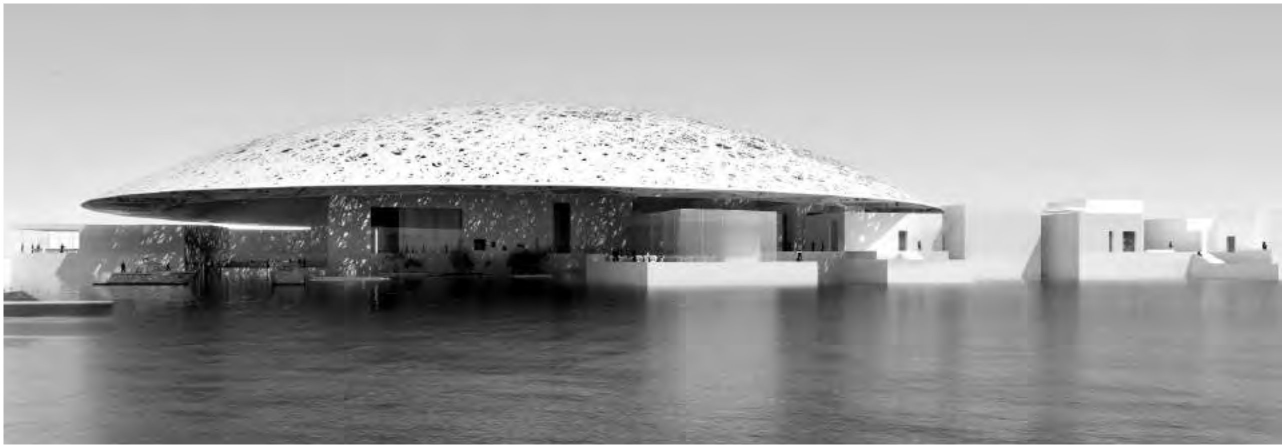
· Macro-scale. The macro-architecture of the entire structure could have a tree-like geometry, described by Constructal theory[7], in order to efficiently collect and transport dew. The Dragon Blood Tree shown in figure 1 is adapted to harvest dew collected from fog and gives an insight into how a dew-harvesting structure might look.

1: The Dragon Blood Tree, found in Yemen, is adapted for harvesting fog-water.

2: Structural optimisation of the dome, enabling effective distribution of material.

3: Illustration of automated patternisation with variable translucency.

4: Perforated multilayered domed roof, Louvre Abu Dhabi.



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DESIGN POTENTIAL FOR LARGE-SCALE ADDITIVE FABRICATION FREE-FORM CONSTRUCTION

XAVIER DE KESTELIER,
FOSTER + PARTNERS

This paper focuses on recent developments in the rapid prototyping and manufacturing industry and specifically in the field of architecture and construction. The paper mainly revisits the idea of a digital design environment for additive fabrication first raised by Buswell and De Kestelier (2009) and possible future developments within that field (Bernaerdt, Van Hauwaert and De Kestelier, 2009). This is then illustrated through the design and construction of an additive fabricated concrete wall component.

FROM RAPID PROTOTYPING TO MANUFACTURING

Rapid prototyping is a fairly new fabrication technology. The first commercially available machines came on the market in the late 1980s and early 1990s.

These first rapid prototyping machines were able to construct physical objects directly from a CAD model. This was done by solidifying a powder or liquid layer by layer. The process adds material incrementally and is therefore also called an additive fabrication process. Prototypes could be made quickly and efficiently directly from 3D digital data. This technology was adopted rather rapidly by mechanical engineers and industrial designers. The material characteristics of these rapid prototyped models were, in the early days, rather poor. They were often brittle and degraded over time (Wohler, 2007).

A lot of research and development has been done in the last two decades on the improvement of the material properties of rapid prototyping technology. Early rapid prototyping machines were only able to produce parts in brittle resins and sintered nylons. It is only in the last decade that materials such as ABS, carbon-reinforced polyamide, polycarbonate and even metals such as titanium and stainless steel can be used (Wohler, 2010). The material properties improved to such a degree that these physical prototypes could often be used as the actual products. This is where the shift from rapid prototyping to rapid manufacturing occurs. Rapid manufactured products are products that are directly fabricated through a layered additive fabrication process. The step from prototype to actual manufactured object is rather small once the material properties of additive fabrication technology improved.


DANGER
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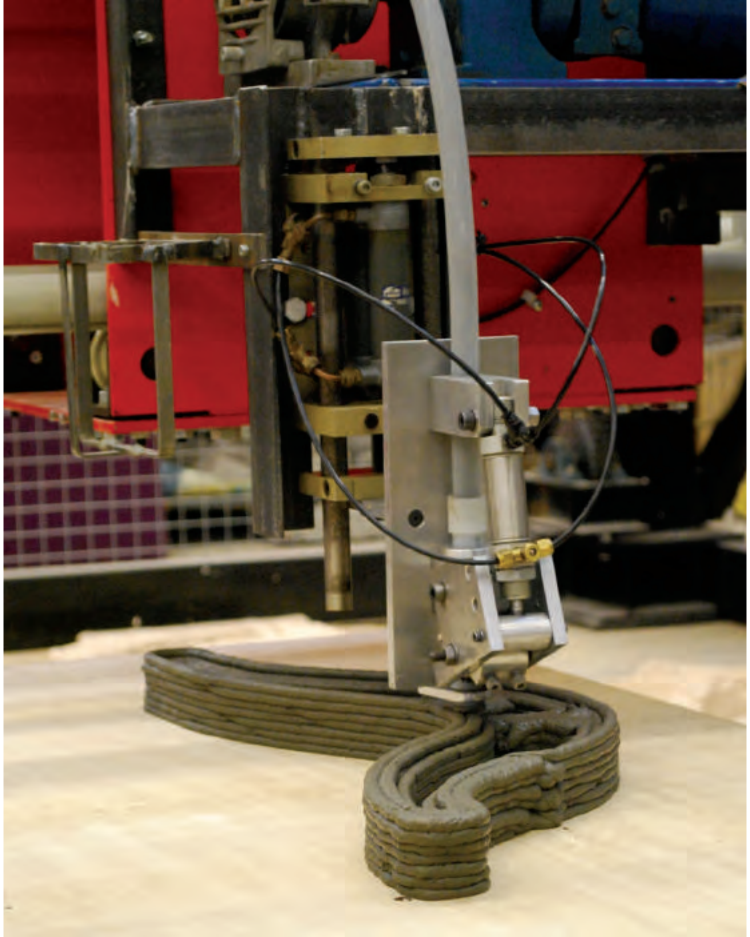

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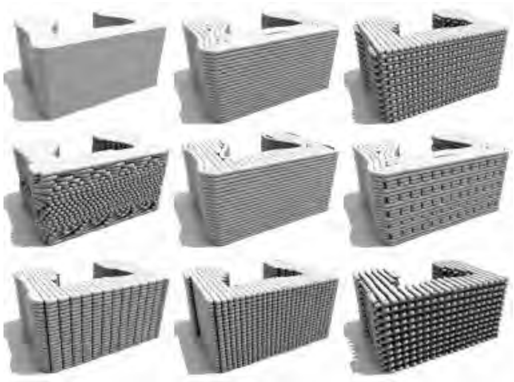

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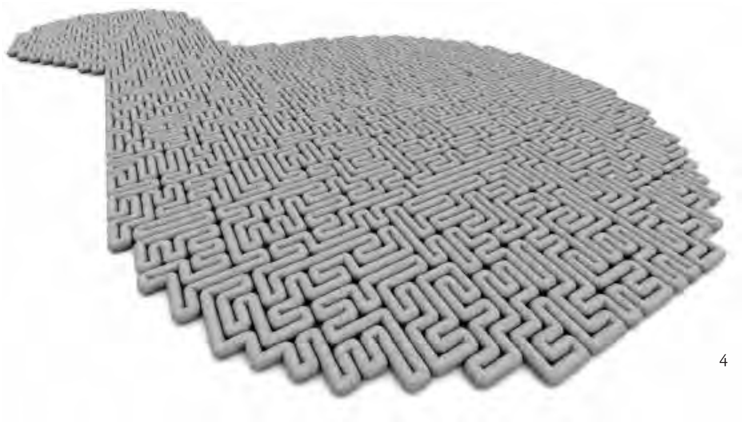

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There are currently a wide range of engineering fields where rapid manufacturing technology has been used: aerospace, automotive (F1), medical tooling, implants, dentistry, etc. These industries often use rapid manufacturing for small production series with a high geometrical complexity. In the last few years a growing number of consumer goods companies have also started to use rapid manufacturing to produce unique high-end designer goods. Examples of these are Freedom of Creation and Materialise.MGX.

In architecture rapid prototyping is used to produce physical scale models. Architectural design practices such as Morphosis (Marty Dosher, 2004) and Foster+Partners (De Kestelier and Peters, 2008) have been the early adopters of this technology. It is only in the last few years that physical model-making through rapid prototyping has become mainstream. It was, for example, only in 2007 that Wohler Associates started to mention 'Architecture and GIS' as a separate industry in their yearly industry report on additive fabrication (Wohler, 2007).

ADDITIVE MANUFACTURING IN ARCHITECTURE

Within the fields of engineering and industrial design, the shift from prototyping towards direct manufacturing was mainly driven by improvements in materials. The step from prototype to actual manufactured object is rather small once the material properties of additive fabrication technology improved. This shift is much more difficult when we try to build architecture instead of architectural models through additive fabrication.

Scale is one of the main differences between industrial design and architecture. Architects are used to work at scale. Drawings and models are always a scaled

1: Large-scale concrete printer that is currently set up at the Innovative Manufacturing and Construction Research Centre (IMCRC) at Loughborough University.

2: Concrete is being extruded through the printing nozzle.

3: Geometrical experiments for extrusion paths for concrete printing.

4: Continuous space-filling extrusion path.

5: A prototype of a wall component was printed on the concrete printer at Loughborough University to demonstrate its current capabilities.

representation of the actual architectural design. The scale of architectural models can easily range between anything from 1:10 to 1:1000. There will need to be a massive scaling exercise to use additive fabrication as a construction technology for buildings or building components. This means that, for architectural projects, a rapid or additive manufacturing process volumetrically typically needs to be scaled up in the order of 10^3 to 10^9.

Since the mid-1990s a few universities and companies have started to attempt to apply additive fabrication in architecture or construction (Gardner, 2009). Three processes are currently actively pursued: Contour Crafting (Koshnevis et al. 2006), D-Shape (Dini et al. 2006), and Free-form Construction (Buswell and De Kestelier, 2009). Contour Crafting has been developed at the University of Southern California by Dr Behrokh Khoshnevis. It is an additive fabrication technique that produces fixed width walls by robotically depositioning an internal and external trowelled skin. The cavity between these skins is then filled with a bulk material through that same robotic arm (Koshnevis et al., 2006).

Enrici Dini has been developing a large-scale fabrication technology that is similar to the 3D printing technology from Z-Corp. It deposits a thin layer of sand over the full bed size of the printer (4 x 4 metres). This sand has been pre-mixed with a catalyst that chemically hardens when it comes into contact with an inorganic binder. This binder is jetted onto the sand through a series of jets. Just as with Z Corp's 3D printing technology, the sand is used as its own support structure.

The Free-form Construction project from Loughborough University will be used in this paper to exemplify the constraints and possibilities of large-scale additive fabrication.

FREE-FORM CONSTRUCTION PROJECT AT LOUGHBOROUGH UNIVERSITY

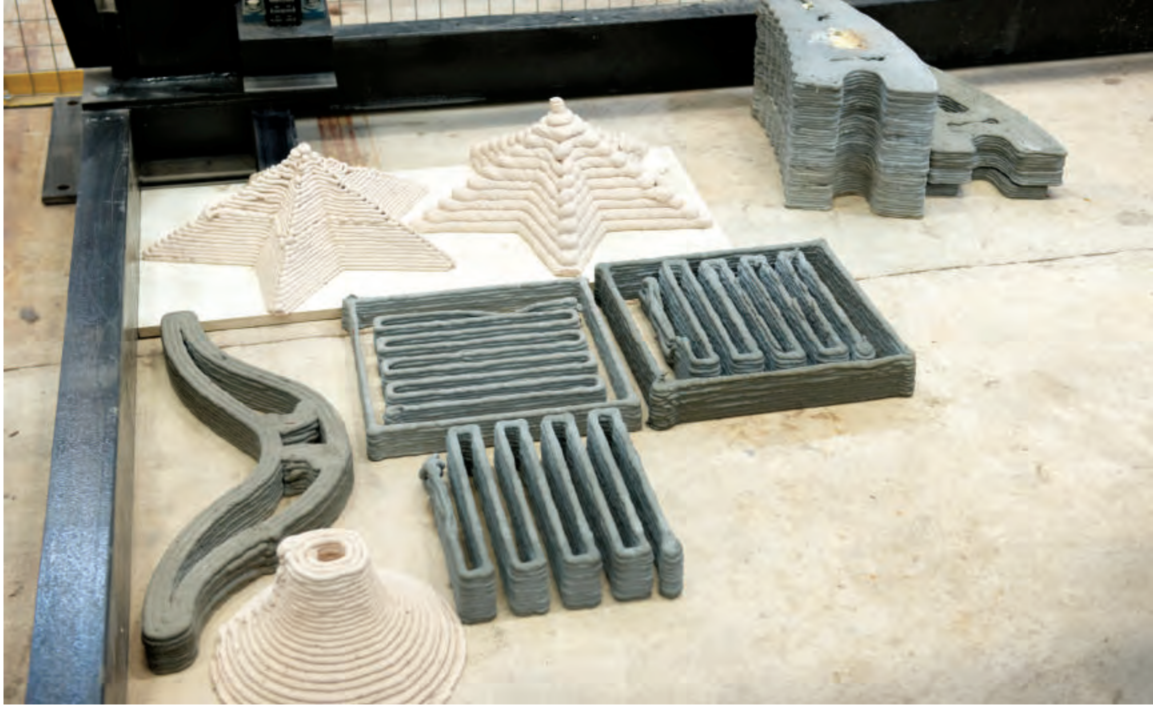
The Free-form Construction project was initiated by the Innovative Manufacturing and Construction Research Centre (IMCRC) at the Loughborough University and is funded by the UK Engineering and Physical Sciences Research Council (EPSRC). It also comprises of a range of industrial partners such as Foster+Partners and Buro Happold.

Over the last four years an additive manufacturing machine has been developed and is capable of producing large (2 x 2 x 2 metres) parts out of concrete. The process deposits concrete through a computer controlled nozzle.

6: Load testing of concrete-printed sample part.

7: Early experiments and sample parts.

8: The tool paths for the concrete printing process were defined by a parametric model in Generative Components and generated by a customised script.



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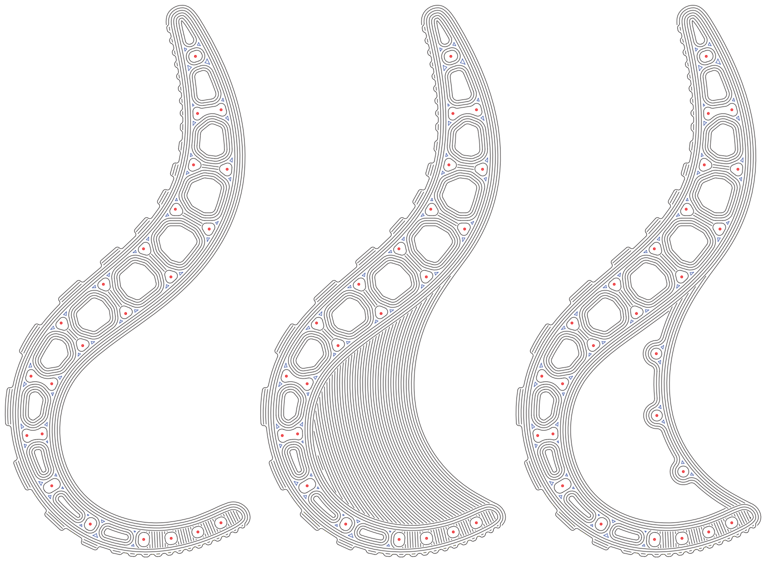
The process can be easily compared to an FDM (Fused Deposition Modelling) technology; with the difference that here concrete is extruded instead of plastic. The concrete is pumped and pushed through a nozzle at a constant speed. A large computer-controlled three-axis steel gantry system deposits this concrete with high precision.

The concrete is deposited without the use of any formwork. Therefore the process allows for an unprecedented freedom in geometrical complexity. As the parts are printed, every single printed part can be different and customised.

THE WALL COMPONENT

To demonstrate these functionalities of additive manufacturing, a wall component was designed and constructed. This component tried to address the new geometrical freedoms that can be associated with additive fabrication. The design for the wall has a varying thickness that can be can be optimised to local loads. There are also cavities in the component that can incorporate services and locally optimised insulation and reinforcement. Due to the geometrical freedom, local optimisations can be achieved through differentiating geometry.

By developing this prototype it became apparent that current standard CAD tools were not sufficient. The



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free-form construction process extrudes concrete in beads with a typical diameter of 9 mm. This is about 100 times larger then current commercially available smaller-scale rapid manufacturing processes. With this process the actual extrusion parts become visible and can even be seen as part of the aesthetics of the part. It is therefore crucial that these paths are taken into account when designing for this large-scale additive manufacturing process. Various experimental extrusion paths were explored as part of a graduation thesis at the Architecture and Urban Design Department of the University of Gent (Bernaerdt, Van Hauwaert and De Kestelier, 2009). These path designs were not developed to optimise for the manufacturing process, but to explore possible design expressions. In most additive fabrication techniques material is added through horizontal layers. This means that tool paths are in fact only in 2D. These studies show that there might be possibilities to explore more complex 3D tool paths.

Taking into account the lessons learned at the University of Ghent, a parametric model was set up in Generative Components to produce the wall component at Loughborough University. It became apparent that a traditional method of modelling, even parametric solid modelling was not going to be sufficient. The design did not only have to define the external volume of the wall but also the actual tool path. The machine tool path became an integral part of the design. The manufacturing process is embedded into the core of the design environment. The tool path model became the parametric design driver as the manufacturing constraints were programmed within that tool path. Slight changes in width of the extruded concrete could, for example, be easily adapted into the parametric model.

Creating the tool paths in a parametric model was not sufficient as it did not visually represent the design. Therefore, each of the tool paths had to be converted into extrusions. This model was then also 3D printed through with a Z-Corp printer.

The workflows for most additive fabrication technologies are quite similar. Typically a design would get modelled up in a 3D CAD package with, preferably, a solids modelling engine. This 3D model is then converted to an STL file. This file format is the standard file format for most additive fabrication processes. An STL file is a very simple low-level file format that stores geometry as a simple set of triangles. Depending on the technology, the STL file will be sliced into horizontal slices. Each of these 2D contoured slices will then have to be filled up and constructed by the additive fabrication machine. Each additive fabrication technology will have its own way of generating a set of machine codes to construct and fill these contour slices (De Kestelier and Peters, 2008).

For the wall component no STL file was generated. The Generative Components model was constructed with tool paths in mind. A set of lines is still not enough information to generate G-code, which could drive the concrete printer. This G-code is a numerically controlled programming language that is widely used to drive CNC machines. To generate this G-code for the concrete printer, a separate software tool was written to convert the line geometry that was generated in generative components into a set of machine instructions or G-code. (Bernaerdt, Van Hauwaert and De Kestelier, 2009). There was no intermediate step needed to go from the 3D model to a set of fabrication instructions. The fabrication technology was embedded within the 3D model and the design process.

This process is, of course, only possible when the designer understands the fabrication technology in detail and when there is a constant interaction between the designer, engineer, programmer and fabricator. It is clear that the development of a new design environment that can embed the possibilities and constraints of additive manufacturing will be crucial in the development of this technology.

END

REFERENCES

RESEARCH PAVILION ICD/ITKE

1 Menges, A., 'Form Generation and Materialization at the Transition from Computer-aided to Computational Design', Detail, English Edn, vol. 2010, no. 04, pp. 330–35.

2 Menges, A., 'Material Information: Integrating Material Characteristics and Behavior in Computational Design for Performative Wood Construction, In:Formation', Proceeding of the 30th Conference of the Association For Computer Aided Design in Architecture (ACADIA) (New York, 28–24 October 2010), pp. 151–158.

3 Menges, A., 'Performative Wood: Integral Computational Design for Timber Construction, Reform: Building a Better Tomorrow', Proceeding of the 29th Conference of the Association For Computer Aided Design In Architecture (ACADIA) (Chicago, 21–25 October 2009), pp. 66–74.

4 Lienhard, J., S. Schleicher, J. Knippers, S. Poppinga and T. Speck, 'Form-finding of Nature Inspires Kinematics for Pliable Structures', in *Proceedings of the International Symposium of the International Association of Shell and Spatial Structures (IASS), Spatial Structures Temporary and Permanent,* ed. Q. Zhang et al. (Shanghai, 2010), p. 501.

THAW IMAGINING A SOFT TECTONICS

1 The textile is developed in collaboration with Prof. Behnam Pourdeyhimi, North Carolina State University, College of Textiles. The material is a blend of polyester and co-polyester. The co-polyester melts at a lower temperature and 'binds' the fibres together. The structure was made by carding crosslapping, followed by needle punching, and then passed through the over to partially melt some of the co-polyester. Prof. Pourdeyhimi used a very special experimental needle that densifies the web to give it density. The web is ~ 300 g/square metre.

2 'Geodetic Construction: Vickers-Wallis System Explained: Advantages of Concentrating Material. Balancing Tension Against Compression', Flight (16 January 1936), p. 67.

3 Graefe, R., 'Vladimir G. Suchov 1853–1939. Die Kunst der sparsamen Konstruktion' (Stuttgart: Deutsche Verlags-Anstalt, 1990).

4 This parametric modelling of the material performance is developed across a series of projects in CITA and has been first implemented in the research workshop 'Digital Crafting: How to Join as Part of a Cross-national Research Network': www.digitalcrafting.dk

5 The research collaboration is part of the Velux Guest Professorship with Prof. Mark Burry, Spatial Information Architecture Laboratory, RMIT, Melbourne. The project is a broad collaboration between the two research centres and includes collaboration with Prof. Mark Burry, Jane Burry, Mette Ramsgard Thomsen, Martin Tamke, Phil Ayres, Alexander Pena, Daniel Davis, Jacob Riiber Nielsen, Stig A. Nielsen, Anders Holden Deleuran, Morthen Winther and Sigurdur Ormarsson.

FABRICATING INDETERMINATE PRECISION

1 Todorov, Tzvetan, *Symbolism and Interpretation,* trans. from Marjorie Perloff, *Poetics of Indeterminacy* (Evanston: Northwestern University Press, 1999)

(FAB)BOTS CUSTOMISED ROBOTIC DEVICES FOR DESIGN & FABRICATION

1 Referring to research conducted by Behrokh Khoshnevis (University of Southern California), Rupert Soar (Loughborough University) and Gramazio & Kohler (ETH Zurich), amongst a growing number of fabrication-related courses and workshops at several universities worldwide.

2 The studios are titled 'Machinic Control 1.0' (AA) and 'Digital Tectonics RS3' (IAAC). The three projects from the AA are produced during a 12-month period of research, while the seven projects from IAAC were conceived in a period of five months. Both design studios supported the work through tutorials in programming and building customised devices using a standard CNC stepper motor control module or the open-source electronics prototyping platform Arduino, which is based on flexible, easy-to-use hardware and software. Student teams were encouraged to benefit from and contribute to a large on-line community sharing experiences with interactive devices and installations.

3 BEAM is an acronym for Biology, Electronics, Aesthetics and Mechanics. This is a term that refers to a style of robotics that primarily uses simple analogue circuits, such as comparators, instead of a microprocessor in order to produce an unusually simple design (in comparison to traditional mobile robots). BEAM robots typically consist of a set of the aforementioned analogue circuits (mimicking biological neurons), which facilitate the robot's response to its working environment.

4 Braitenberg Vehicles are conceived by the Italian-Austrian cyberneticist Valentino Braitenberg and illustrate the abilities of simple agents. The vehicles represent the simplest form of behaviour-based artificial intelligence or embodied cognition; that is, intelligent behaviour that emerges from sensorimotor interaction between the agent and its environment, without any need for an internal memory, representation of the environment or interference.

5 BOIDS is an artificial life program, developed by Craig Reynolds in 1986, which simulates the flocking behaviour of birds. As with most artificial life simulations, BOIDS is an example of emergent behaviour; that is, the complexity of BOIDS arises from the interaction of individual agents (the BOIDS, in this case) adhering to a set of simple rules.

CNCATENARY TOWARDS A DIGITAL FABRICATION METHOD FOR CATENARY SYSTEMS

1 Chak, D., M. Galbraith and A. Kilian, 'CatenaryCAD: An Architectural Design Tool' final project report for a class on computer graphics, MIT (2002)

MATTER & MAKING

1 'The 2003 Inductees', The Robot Hall of Fame Webpage, The School of Computer Science at Carnegie Mellon Universtity: www.robothalloffame.org/unimate (accessed 5 December 2010).

2 The designed wind was calculated for a reduced wind speed of 50 mph yielding a pressure of approximately 5 psf. For reference, the Safir-Simpson Hurricane Scale defines winds of 50 mph as a tropical storm.

3 A Change of State is constructed of polyurethane sheet material. The sheets were CNC profile cut into custom construction units. These units were cold bent, twisted and bolted to their neighbours to occupy the third dimension. By aggregating this system, volume was occupied in the form of a space truss spanning a full column bay.

4 Drawn Dress is an interdisciplinary project addressing the custom needs of dress design with advanced

technologies such as digital body scanning and CNC fabric cutting. The designs produced during the project all hug tightly to the body as a way of testing the precision and fit, though they leave the body to enter the volumetric space of digital modeling. The seams of these dresses are truly 3D and are conceived of as volumetric objects, though implemented through 2D patterns.

5 AtmoSPHERE is a proposal for a building envelope for a factory building in Los Angeles. This proposal questions the idea that building envelopes need to be hermetic seals. Instead, when given depth, an envelope could perform closer to a sponge or the leaves of a tree. This volumetric envelope shades the interiors, while allowing ventilation to move freely through the envelope and condition through its filtering technique.

6 This research is not obligated to EPS foam as a material, but rather volumetric materials as a larger category. While EPS foam was used for this case study, further research is taking place to engage these other volumetric materials listed.

7 The EPS foam for Periscope was sourced in Michigan, fabricated in there, and transported to Atlanta. Sourcing is Atlanta was possible; however, the fabrication facilities available to the project in Atlanta were not equipped to handle the material or the method developed. As a proposal for a larger making process, it must be clarified there is an assumption that these fabrication techniques would be local as well.

8 Stereotomy is the technique of cutting solids to specific forms and dimensions.

9 Evans, Robert, 'Drawn Stone', in *The Projective Cast: Architecture and Its Three Geometries* (Cambridge, MA: MIT, 1995), print.

10 For the stonemason, this line was not a physical object, but rather a geometric principle allowing 2D traits to describe a 3D form. The hot-wire performed as this principle in real time.

TERRA THERMA

1 See www.water-technology.net/projects/thameswater

INVESTIGATIONS IN DESIGN & FABRICATION AT HYPERBODY

1 Arduino is an open-source electronics prototyping platform, for more information please see: www.arduino.cc

2 NedCAM is a company based in the Netherlands that specializes in large-scale CNC fabrication and have worked on a number of interesting architectural projects. Its important to point out that NedCAM has been experimenting with hot-wire cutting for the roughening foam blocks that will be further milled.

LARGE, COMPLEX, PERFORATED ENCLOSURES IN EXTREME ENVIRONMENTS CONTROL OF STRUCTURAL & THERMODYNAMIC BEHAVIOUR, FROM MACRO TO NANO-SCALE

1 Baker, W. F., *Stiffness Optimization Methods for Lateral Systems of Buildings: A Theoretical Basis, Electronic Computation, 21 Buildings, Towers and Tanks* (CE) (1991), pp. 269–78.

2 Almarshad, A. I., and S. Syed, 'Atmospheric Corrosion of Galvanised Steel and Aluminiumin Marine and Marine-industrial Environments in Saudi Arabia', *Materials & Corrosion,* vol. 59, no. 1. (2008).

3 Monteith, J. L., and M. H. Unsworth, *Principles of Environmental Physics,* 3rd Edn (Academic Press, 2008).

4 de Villiers, M. P., and J. van Heerden, 'Fog at Abu Dhabi International Airport', *Weather* (2007), vol. 62, no. 8, pp. 209–14.

5 Nosonovsky, M., and B. Bhushan, eds, Theme Issue 'Green Tribology', Phil. Trans. R. Soc. A. (28 October 2010), vol. 368, no. 1929.

6 Bejan, A., and S. Lorente, 'The Constructal Law of Evolution in Design and Nature', Phil. Trans. R. Soc.B (12 May 2010), vol. 365, n13th of May 2008.

7 Ibid.

FURTHER READING

CNCATENARY TOWARDS A DIGITAL FABRICATION METHOD FOR CATENARY SYSTEMS

Gramazio, F., and M. Kohler, *Digital Materiality in Architecture* (Baden: Lars Müller Publishers, 2008).

Chak, D., M. Galbraith and A. Kilian, 'CatenaryCAD: An Architectural Design Tool' final project report for a class on computer graphics, MIT (2002)

Kolarevic, B., 'Information Master Builders', in *Architecture in the Digital Age: Design and Manufacturing,* ed. Kolarevic (New York: Spon, 2003)

DESIGN FOR POTENTIAL LARGE-SCALE ADDITIVE FABRICATION FREE-FORM CONSTRUCTION

Bernaerdt, S., K. Van Hauwaert and X. De Kestelier, 'Large-scale Rapid Manufacturing for Construction Industry: The Architecture of a New Design Environment', unpublished dissertation at the Department of Architecture and Urban Design, University Ghent (2009)

De Kestelier, X., and B. Peters, 'Rapid Prototyping and Rapid Manufacturing at Foster+Partners', Proceeding of the ACADIA 2008 Conference Minneapolis: Proceedings of the 28th Annual Conference of the Association for Computer Aided Design in Architecture(ACADIA) (2008)

De Kestelier, X., and R. A. Buswell, 'A Digital Design Environment for Large-scale Additive Fabrication', Proceeding of Arcadia 2009, reForm conference (Chicago, 22 October 2009)

Dini, E., R. Nannini and M. Chiarugi, 'Method and Device for Building Automatically Conglomerate Structures', WO Patent WO/2006/100,556 (2006)

Gardiner, J., 'Sustainability and Construction-Scale Rapid Manufacturing: Opportunities for Architecture and the Construction Industry' Proceeding of RAPID 2009 Conference (17 June 2009)

Khoshnevis, B., D. Hwang, K. T. Yao and Z. Yeh, 'Mega-scale Fabrication by Contour Crafting', *International Journal of Industrial and Systems Engineering,* (2006), no. 1, pp. 301–20

Dosher, M., 'Modelling in a Digital Dimension', Designbuild-network: www.designbuild-network.com/features/feature75564 (accessed 1 December 2010)

Wholers, T., *Rapid Prototyping, Tooling and Manufacturing: State of the Industry* (Colorado: Wohlers Associates, 2010)

END NOTES

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Responsible for the scientific development were Moritz Fleischmann (project management), Simon Schleicher (project management), Christopher Robeller (detailing/construction management), Julian Lienhard (structural design), Diana D'Souza (structural design) and Karola Dierichs (documentation).

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LINKS
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THAW IMAGINING A SOFT TECTONICS

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Thaw was exhibited as part of the digital material exhibition at R.O.M Gallery for Art and Architecture, Oslo, in May 2010. The exhibition was kindly supported by the Nordic Culture Foundation and Henrik de Miniassen, director of R.O.M. Thaw was further developed as a larger-scale installation for the Lisbon Architecture Triennale as a 10-metre-high installation Thicket.

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(FAB)BOTS CUSTOMISED ROBOTIC DEVICES FOR DESIGN & FABRICATION

Design Studio: 'Machinic Control 1.0': Tutors: Marta Malé-Alemany, Jeroen van Ameijde. Architectural Association School of Architecture, Design Research Lab (DRL) Graduate Programme (2009–10). Projects: DIGITAL VERNACULAR: Shankara S. Kothapuram, Mei-ling Lin, Ling Han, Jiawei Song. FIBR(H)OUS(E): Amrita Deshpande, Saahil Parikh, Akhil Laddha. FLUID CAST: Ena Lloret, Maria Eugenia. Villafañe, Jaime De Miguel, Catalina Pollak. Design Studio: 'Digital Tectonics RS3', Tutors Marta Malé-Alemany, Victor Viña, César Cruz Cazares (assistant), Lluís Fraguada (collaborator). Institute of Advanced Architecture of Catalonia (IAAC), Master in Advanced Architecture (2009–10). Projects: SANDBOT: Joel Letkemann, Viraj Kataria, Fabio Lopez. HELIOBOT: Felipe Pecegueiro, Jorge Orozco, Kfir Gluzberg. FAB [A]THING: Jun Huang, Jessica Lai, Asim Hameed. DREAMWEAVER: Melat Assefa, Brian Peters, Joao Albuquerque. NGPS: Ali Basbous, Miquel Lloveras. PNEUMORPHOSYS: Natalija Boljsakov, Brian Miller, Carlos Naranjo. MIMICRY: Mia Gorretti Layco, Georgia Kotsari, Tomasz Starczewski. Exhibition: (FAB)BOTS, Customized robotic devices for design and fabrication, 16 June to 12 September 2010, Disseny Hub Barcelona (DHUB). Curator: Marta Malé-Alemany. Coordination: Catalina Pollak.

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CNCATENARY TOWARDS A DIGITAL FABRICATION METHOD FOR CATENARY SYSTEMS

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FREE-FORM METAL INFLATION & THE PERSISTENT MODEL

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Persistent Model #1 was an exhibit in the show entitled *digital.material* which showcased four recent works by CITA. The exhibition ran from 23 April to 23 May 2010 at the ROM Gallery, Oslo.

MATTER & MAKING

PERISCOPE FOAM TOWER

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PROJECT CREDITS
Design Team: Matter Design – Brandon Clifford, Wesley McGee. In collaboration with Supermanoeuvre – Dave Pigram. Structural: Simpson Gumpertz&Heger – Matthew Johnson. Build Team: Matter Design – Brandon Clifford, Wesley McGee, Johanna Lobdell, Deniz McGee, Kris Walters, Maciej Kaczynski. Rigging: Boutte Tree – TiersonBoutte. Fabrication: University of Michigan Taubman College of Architecture and Urban Planning.

WAVE PAVILION

Designer/Fabricator: macdowell.tomova. Consultants: Wes McGee, Matter Design; Dave Pigram, Supermanoeuvre.

BENT

Kendra Byrne and Nick Rebeck: www.b-e-n-t.com

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MATERIAL ANIMATION A NEW INTERFACE TO CUSTOM FABRICATION

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MINIMAL COMPLEXITY

The Minimal Complexity prototype was developed during the Certificate of Advanced Architectural Research Postgraduate Course at The Bartlett,UCL, between 2009 and 2010, and it has taken part in 'Constructing Realities', the final exhibition of the Course's research work between July and October 2010.

The theoretical paper 'Minimal Surfaces as Self-Organizing Systems' describing the computational framework for generating the final prototype was developed as part of the MSc. Adaptive Architecture and Computation Course at The Bartlett, UCL, 2009, and has been presented at ACADIA Conference, in New York, in October 2010.

The Minimal Complexity structure winner of the TEX-FAB REPEAT Digital Fabrication Competition was built in Houston, Texas, in February 2011.

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INVESTIGATIONS IN DESIGN & FABRICATION AT HYPERBODY

PROTODECK

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PROTOSPACE 4 MOCK-UP

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PROJECT CREDITS
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PROTOTYPE FOR A SPATIALISED INSTRUMENT

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VILLA NURBS

City: Empuriabrava. Country: Spain. Construction: started 2003. Office: Cloud 9 (Barcelona, Spain; est. 1997) Architect: Enric Ruiz Geli. Collaborators: Felix Fassbinder (Project Architect), Jordi Fernández Río (Project Architect). Arquitectos Técnicos: Daniel Benito Pò (Architect), Xavier Badia (Architect), Agustí Mallol (Architect), Víctor Llanos (Collaborator [office]), Miguel Carreiro (Collaborator [office]), Emmanuel Ruffo (Collaborator [office]), Rosa Duque (Collaborator [office]), André Macedo (Collaborator [office]), Ura Carvalho (Collaborator [office]), Hye Young Yu (Collaborator [office]), Marta Yebra (Collaborator [office]), Mae Durant (Collaborator [office]), Angelina Pinto (Collaborator [office]), Randall Holl (Collaborator [office]), William Arbizu (Collaborator [office]), Max Zinnecker (Collaborator [office]), Laia Jutgla (Collaborator [office]), Manel Soler (Collaborator [office]), Megan Kelly-Sweeney (Collaborator [office]), Alessandra Faticanti (Collaborator [office]), Susanne Bodach (Collaborator [office]), André Brosel (Collaborator [office]), Konrad Hofmann (Collaborator [office]), Nora Graw (Collaborator [office]), Cricursa/Vicky Colombet (Glas Manufaturer), Toni Cumella Ceramic Manufacturer), Frederic Amat (Ceramic Artist), Industrias de la Fusta (IFV) (Corian Manufacturer), Covertex (ETFE Manufacturer), BOMA SL (Engineering), Obres i Construccions Joan Fustè (Construction), Diorama (Wood), Calderería Delgado (Steel Framework), Ramón Presta (Hydraulics), Industrias BEC (Tensile Structures), Aiterm, PGI, Reindesa (Installations), Aislater, Inoxcolor (Installations), Estudi Ramon Folch (Construction), Emiliana Desigestudio (Graphic Design), BAF (Audiovisuals), Led's Go (Illumination). Client (Private): Family Emilio Gallego. Programme: housing.

C-STONE & C-BENCH

This project is dedicated to Christel Vandewaerde (4 December 1963 – 18 December 2010).

GALAXY SOHO LARGE-SCALE CLADDING CONSTRUCTION IN CHINA

Client: SOHO China Ltd., Beijing, China. Architect: ZAHA HADID ARCHITECTS. Design: Zaha Hadid with Patrik Schumacher. Project Associate: Cristiano Ceccato. Project Director: Satoshi Ohashi. Project Architect: Yoshi Uchiyama. Project Manager: Raymond Lau. Project Team: Stephan Wurster, Michael Hill, Samer Chamoun, Eugene Leung, Rita Lee, Lillie Liu, Rolando Rodriguez-Leal, Wen Tao, Tom Wuenschmann, Seung-ho Yeo, Shuojiong Zhang, Michael Grau, Shu Hashimoto, Shao-Wei Huang, Chikara Inamura, Lydia Kim, Yasuko Kobayashi, Wang Lin, Yereem Park, Christoph Klemmt, Dorian Bybee, Kyla Farrell, John Klein. Local design institute:

BIAD (Beijing Institute of Architecture and Design), Beijing. Facade engineer: KT Kighton Ltd., Shanghai. Timeframe: 2008–12. Programme: Mixed-Use Commercial & Retail Complex, Shell & Core Fit-Out. GFA: 360,000m2 + 150,000m2 Below Grade. Site Area: 50,000m2. Height: 67 metres = 16 Floors Above Grade.

MEDIA-ICT

City: Barcelona. Country: Spain. Completed: January 2010 (started 2005). Office: Cloud 9 (Barcelona, Spain; est. 1997)

Architect: Enric Ruiz Geli. Collaborators: Josep María Forteza (Building advising), Agustí Obiol (Structural engineering), David Tusset (Engineering), Hector Yuste (Project management), Joan Buj Cotes (Construction), Carlos Siscart González (Construction), Ben Morris (Construction), Lluis Renom (Construction), Edouard Cabay (Architect), Javier Pérez Contonente (Architect), Francesco Ducato (Architect), Felix Fassbinder (Architect), Nora Graw (Architect), Konrad Hofmann (Architect), Victor Llanos (Architect), Max Zinnecker (Architect), Marta Arranz (Collaborator [office]), Ruben Alonso (Collaborator [office]), Luis Borunda (Collaborator [office]), Marta Banach (Collaborator [office]), Daniel Corsi (Collaborator [office]), Cristina Guadalupe (Collaborator [office]), Albert Lopez (Collaborator [office]), Mireia Luzarraga (Collaborator [office]), Patricio Levy (Collaborator [office]), Alex Muiño (Collaborator [office]), Beatriz Minguez (Collaborator [office]), Veronica Mansilla (Collaborator [office]), Federico Ortiz (Collaborator [office]), Mireia Pallarès (Collaborator [office]), Marisol Verges (Collaborator [office]), Hale YoungBlood (Collaborator [office]), Pep Bou (Art), André Macedo (Design). Client (Public): Consorci de la Zona Franca and 22@. Programme: Office.

THE SPHERE GENERATE, FABRICATE, CALCULATE

The authors would like to thank Oliver Drawer and Arnold AG for the successful collaboration during planning and construction. Their commitment is visible in the quality of the finished object. We would also like to thank Giulio Castegini , the project manager from Mario Bellini Associati S.r.l. for his untiring dedication to achieving the maximum quality.

WAVED WOODEN WALL

Kilden Performing Arts Center, Kristiansand, Norway. Architect: ALA Arkitekter AS, Helsinki, Finland. General Contractor: AF Gruppen AS, Oslo, Norway. Timber Facade Contractor: Trebyggeriet SA, Hornnes, Norway. FaCade Cladding, CNC-Fabrication: Risør Trebåtbyggeri AS, Risør, Norway. Facade Structure, CNC-Fabrication: Blumer-Lehmann AG, Gossau, Switzerland. Façade Engineering: SJB Kempter-Fitze, Eschenbach, Switzerland. Consulting, Digital Planning: designtoproduction GmbH, Erlenbach/ Zurich, Switzerland.

LOUVRE ABU DHABI 1:33 LIGHT-TEST PROTOTYPE

Construction of the 1:33 prototype has been a cooperation between: 1:One | Computational Geometry (programming), George Ackermann GmbH (manufacturing & assembly) and Honkahe Interior+Furniture (modelmaking and consulting).

PHOTO CREDITS

RESEARCH PAVILION ICD/ITKE

A. Menges, 2010: 1, 7; C. Robeller/S. Schleicher, 2010: 2, 3; A. Eisenhardt/M. Vollrath/K. Wächter/S. Schleicher, 2010: 4; A. Lautenschlager, 2010: 5; A. Eisenhardt/M. Vollrath/K. Wächter, 2010: 6,9; S. Schleicher, 2010: 8.

UNIKABETON PROTOTYPE

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FREE-FORM METAL INFLATION & THE PERSISTENT MODEL

Anders Ingvartsen: 1, 3; Anders Holden Deleuran, CITA: 5.

MATTER & MAKING

PERISCOPE FOAM TOWER

Matter Design, 2010: 1, 2, 4, 5, 6, 7; FABLab University of Michigan Taubman College of Architecture and Urban Planning, 2010: 3.

BENT

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MATERIAL ANIMATION A NEW INTERFACE TO CUSTOM FABRICATION

Greg Epps, 2010: 1; Nick Puckett, 2010: 3.

INVESTIGATIONS IN DESIGN & FABRICATION AT HYPERBODY

Jelle Feringa, 2010: 1, 6, 7, 8, 9, 10; MarkDavid Hosale, 2010: 2; MarkDavid Hosale/ Marco Verde, 2010: 3; Jan Jacobs, 2009: 4; Marco Verde, 2010: 5.

KOHLER/KARA

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GALAXY SOHO LARGE-SCALE CLADDING CONSTRUCTION IN CHINA

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MEDIA-ICT

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THE SPHERE GENERATE, CALCULATE, FABRICATE

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THE RICHMOND SPEED SKATING OVAL ROOF

Fast + Epp Engineers: 1; StructureCraft Builders: 2–8.

THREE PROJECTS A COMPARITIVE STUDY

Amanda Levete Architects: 1, 3, 4, 5, 6, 7, 8, 10; Edmund Sumner: 2; Leo Torri for DuPontTM Corian®: 9; © Meinhardt Façade Technologies: 11.

MULTI-SPHERICAL MIRRORED SCULPTURE

M. Hess photography: 1; Arup photography: 2, 3, 4, 7.

MÉDIACITÉ

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RADIOLARIA PAVILION

Credit: Blueprint, 2009: 1; Credit: Shiro Studio: 2, 4; Credit: D-Shape, 2009: 3, 5, 6.

WAVED WOODEN WALL

1, 2 © Trebyggeriet; 3, 4, 5 © designtoproduction.

RUAIRI GLYNN

Ruairi Glynn is Lecturer in MSc Adaptive Architecture and Computation, and tutors the MArch Architectural Design Programme at The Bartlett School of Architecture, University College London. He is Associate Lecturer in MA Textile Futures and MA Industrial Design at Central Saint Martins, University of Arts London. Collaborating across design disciplines through digital and analogue practices, he and his students develop responsive environments, from hybrid materials and software systems up to architectural scale installations. He has run workshops and acted as visiting lecturer to leading centres of architectural and computational design including ETH Zurich, TU Delft, and CITA Copenhagen.

In 2010 he was awarded an Engineering & Physical Sciences Research Council scholarship to support doctoral research on the animation of architecture through robotics. Since 2005 he has been developing a series of interactive environments titled '*Performative Ecologies*'. His work examines gestural interaction between inhabitant and architecture, through the use of sensory and servo motor actuated systems. Recent exhibitions include the Los Angeles' 'Beall Centre of Art & Technology', Seoul's 'SOMA', São Paulo's 'Itaú Cultural' and Madrid's 'International Contemporary Art Fair', leading to a international awards including the '*Europrix*', European Award for Digital Media and the '*Concurso Internacional de Arte y Vida*'.

In 2009, he was organiser of the multidisciplinary '*Digital Architecture London Conference*' at the Building Centre. Divided into panels on Space, Biotechnology, Interaction, Form and Fabrication, London's leading Architects, Artists, Interaction Designers, and Scientists were invited to discuss the state of the art, the similarity and differences between approaches and to speculate on post-digital futures. Bringing together work of London's leading Architecture Schools, the AA, Bartlett, RCA and Westminster, a complimentary exhibition '*Digital Hinterlands*' co-curated with Jennifer Greitschus was held at London's *Phase 2* Gallery. '*Digital Architecture, Passages Through Hinterlands*' co-authored with Sara Shafiei and designed by Emily Chicken was published in parallel.

BOB SHEIL

Bob Sheil is designer, maker and educator. He is Senior Lecturer and Director of Technology and Computing at The Bartlett School of Architecture UCL, where he also runs MArch Unit 23 with Emmanuel Vercruysse, a workshop based unit exploring relationship between the digital and analogue in issues such as craft, prototyping and adaptive architecture. In 2007 he was awarded funds of £0.5m and established The Bartlett's Digital Manufacturing Centre, representing the school's most significant new investment in decades. He has lectured extensively in the UK and overseas, and is an active contributor towards evolving architectural education at a national level.

He founded sixteen*(makers) with Nick Callicott in the mid 1990's, later to be joined by Phil Ayres, Chris Leung and Vercruysse. Their most recent work, '55/02', a forestry shelter in Kielder Park, Northumberland UK is an exploration of digital design and manufacturing, in collaboration with manufacturers Stahlbogen GmbH, of Blankenburg, Germany. A monograph on '55/02' will be published this year through Riverside Architectural Press.

Sheil has authored and edited a number books, papers and articles on his interest in the relationship between design and making, including two guest edited issues of AD 'Protoarchitecture-between the Analogue and the Digital' (2008) and 'Design through Making' (2005). In 2011 he will complete a collection of 16 critical essays by pioneers in design and making, including Peter Salter, Rural Studio and Mark Burry, in 'Manufacturing the Bespoke' an AD Reader published by Wiley.

His latest design and build project, for a mobile performance space, is a collaboration with former Unit 23 students and the Central School of Speech and Drama, it was presented at the Adaptive Architecture Conference March 2011, and will be exhibited and presented at the Prague Quadrennial of Performance Design and Space.

EDITORS BIOGRAPHIES

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