Periodica Polytechnica
Architecture

47(2), pp. 79-88, 2016
DOI: 10.3311/PPar.10203

RESEARCH ARTICLE

Intelligent Making and Robotic Structure

Yan Gao[1*], Xin Guo[2], Victor Leung[3]

Received 23 October 2016; accepted after revision 09 December 2016

Abstract

This article proposes a more design-orientated making process with the emerging robotic technologies through the "Intelligent Wave Project" (IWP).This research project went through three stages including physical experimentation, computational simulation, and the design & making of a robotic installation. The research process synthesises abstract geometries, Complex System Theory, 3D Print, and automatic control through computational protocols. The core objective of the IWP is to achieve a self-supporting surface mass from a simple rule-based component system that transforms its shape. The breakthrough of this robotic installation is that the identical cells that are repeatedly connected under the reciprocal frame principles and the triangulated geometry constraints are capable of generating emerging global reconfigurations of both the spatial structure and the intricate geometric pattern. The surface responds to different external forces accordingly, i.e. the location, the intensity and the sequence of the force. Such behaviour is scripted into the digital modelling before the realisation of the final programed structure. Instead of using dynamic pistons, the transformation is achieved through local sliding and rotating in particular sequences; these trigger the global surface transformation into either concave or convex. This article also compares the above research project with the concurrent experiments of robotic applications in architectural research. It embraces design intelligence for a more holistic perspective in order to explore the meaningful and applicable design opportunities for the future of architectural robotics.

Keywords

Robotic Structure, Intelligent Fabrication, Complex Behaviour, Surface Transformation, Self-organised Complex System, Design Orientated Research

[1] Department of Architecture, University of Hong Kong
[2] Department of Architecture, University of Shenzhen
[3] Media Lab, Massachusetts Institute of Technology
[*] Corresponding author, e-mail: yangao@hku.hk

1 Introduction

Today, science and technology is in a continuous process of rapid and constant development, not only penetrating the professional AEC[1] industry but increasingly infiltrating the field of architectural research. This is illustrated by the digital representation of complex and plastic form. Greg Lynn theorised form based on the composite thinking that led to the fusion of disparate elements into thinner, lighter, stronger surfaces and shells (Lynn, 2012). While Achim Menges utilising current computational design processing and material-oriented fabrication has provided architecture with new modes of integrating design techniques, production technologies and system performance (Menges, 2012). The application of machines in the fabrication process has been upgraded from the 3-axis Numeric Control (NC) devices like CNC Routers to the new wave of using industry robots (often minimum 6-axis), which opens up more possibilities in accomplishing far more complex fabrication tasks. The use of a robotic arm has therefore announced the arrival of Robotic Architecture to the pioneering research in architectural design and fabrication.

In contrast to the above robotic approach in architectural research, which is the application of the articulated robotic arm to produce static architecture, this article discusses the other approach of designing and making a dynamic architecture which can physically change its shape. This was illustrated in the Intelligent Wave Project (IWP), a design research project exhibited in the Robotic Future 10th Shanghai Biennale 2014 City (Anon, 2014). IWP has the potential to achieve "the inclusion of robotic elements as integral parts of built environment" (Apoorva Kapadia), as it investigates the design, fabrication and assembly of a reconfigurable self-supporting surface that is automatically controlled through programming; thus, a self-supporting surface assembly that behaves like a robot.

2 Towards the Architectural Robotics

The IWP addresses the view of William Mitchell who ever stated that "The building of the near future will function more

1 Architecture, Engineering and Construction and more like large computers" and that "Our buildings will become…robots for living in" (Mitchell, 2000). His statement implies the following two general approaches to associate robotics with architecture; "the first to add sensory/computational elements to existing architecture (smart buildings) (Johanson et al., 2002), and the second to introduce self-contained robots into existing spaces," (Streitz et al., 2002; Kapadia et al., 2010). The first approach will barely effect a formal or spatial change in architecture, hence is less interesting for architects. The second approach evokes a more integrated spatial experience in architecture with the robotic process inseparable from the architectural design, as it relies on the dramatic physical change of the building mass, achieving a continuum robot (Walker, 2001), or the "blob" architecture as defined by architect Greg Lynn, "connotes a thing which is neither singular nor multiple but an intelligence that behaves as if it were singular and networked, but in it form can become virtually infinitely multiplied and distributed" (Lynn, 1988).

A number of precedents in the second approach have been piloted. This includes Oosterhuis' real-time pavilion series, including the Hydra in his Salt Water Pavilion, which transmits information in the form of sound and light as a response to visitors (ONL, 1997), and the "Muscle Body" pavilion (Hyperbody Research Group, 2005, Fig. 1). The latter is capable of transforming its shape through bendable tubes driven by 26 industrial "Festo muscles" (Hubers, 2005). The Digital Water Pavilion for Expo 2008 continues the exploration in "How to make fluid, reconfigurable architecture?" (Ratti, 2008) by digitally controlled waterfall (Fig. 2). The "Responsive Environment" series at AA Design Research Laboratory has cast seeds in exploring the transformable built environment conceptual prototypes. (AA DRL, 2001-2003). The IWP is one of those prototypes that was eventually realised after ten years thanks to the development of computational instruments. The Wave Garden (Fig. 3) even expands the robotic concept to the landscape field in urban scale (Obuchi, 2005).

Fig. 1 The Muscle Body by The Hyperbody Research Group

Fig. 2 The Digital Water Pavilion by C. Ratti

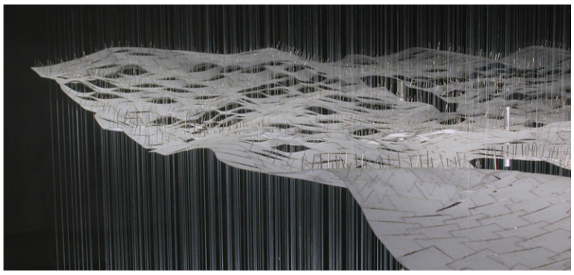

Fig. 3 The Wave Garden by Yusuke Obuchi

All these research projects endeavoured to pioneer research in creating fluid architecture that resembles robotic behaviour. However, due to the extreme difficulty in reorganising architectural structure elements and existing construction technologies, the research either has to rely on high-tech materials or mechanical systems unavailable to the architectural field; otherwise, the operations can only apply to the "skin" medium around the architectural space, such as sound, light, or water for visual effect, etc. In this direction, the architectural value in conceptualising materialisation processes and synthesising structure, space and form are overridden by the exceptional expertise of the science in engineering, materials and computing. The power of architectural intelligence in constructing ideas and material processes to structure meaningful space suffers from the exclusive concentration in the technique as the content of the design, which currently dominates the field of robotic architecture.

In response, IWP neither follows the path of interactive architecture which often scratches the "skin" of space for visual effect or informational images, nor continues the prevailing approach of applying the technology and process of industry robots to produce the same concept of architectural canopies. IWP looks into the core of architecture, i.e. the "bones" of space, with the digital fabrication through design intelligence but not the machine power. We need to clarify what is design intelligence in the context of digital fabrication.

3 Design Intelligence in Digital Fabrication

Over the past ten years, from different perspectives and occasions, as the witnesses and participants in the rise and fall of different technological factions between the developed and the developing world, we have a persistent question constantly hovering; what indeed defines architects from other professionals if they commit to the trans-disciplinary world of digital fabrication and robotics. In other words, when architects work on robots, they have little chance to excel over robotic engineers and computer scientists in terms of techniques and technologies. The architectural collaboration on robotic arms pales in comparison with automobile production line robots that have been in use for years. Therefore, if architects endeavour to develop or use robots, they must make spatial products that are profoundly different from the work of industrial engineers.

Although increasingly embracing digital fabrication, architects will, sooner or later, reach a bottleneck and exhaust eye-catching forms, unlike artists who can barely empty their creativity in object scale while enjoying the liberty of little functional or structural constraints. Meanwhile, architects' interest in the precision and efficiency of digital fabrication for building smartly, rapidly, and economically will not necessarily enable the architects' leading role.

So, if neither the novelty in creating a complex form, nor the precision and efficiency that defines the architects' essential value, what is it then? How can architects position themselves as an expert in the present digital workflow for building projects? It is the design intelligence and synthesis that underwrites the most remarkable merits of architects, i.e. their ability to design space, within the multi-dimensional constrains, through the integrated and complex workflow. Within this "geometric, spatial and technical information is filtered through simulation, analysis and optimisation processes, with the aim to form integrated building information models that can generate an array of output ranging from energy usage to manufacturing instructions" (Marble, 2012), to reflect the design concepts that address cultural, social, environmental, economic and sometimes even political relevance. As Ben van Berkel says, "the essence of architects correlates with craftsmen's imaging, reflecting and the capability to deal with things" (Berkel, 2012).

No doubt that digital fabrication has expanded the scope of architects' control and involved them in the big ensemble of scientific knowledge on the collaborative network of expertise. Whereas, such expertise in digital fabrication does not and cannot replace the essence of architectural design in pursuing design ideas, opening access to wider resources, and increasing the possibilities for innovative large-scale architectural artefacts. It would be problematic if the realm of digital expertise overturned the architects' ability for thinking and sensibility of judging; their design philosophy would fall into the material ONLY driven process, ignoring the humanistic dimensions. Herein are some examples of design intelligence in digital fabrication, providing a design solution that

- is a freeform surface assembly made of identical components with adaptable joints instead of hundreds of thousands of unique components
- achieves a freeform surface with planar shape or straight components instead of heavily bent or twisted cells
- has a repetitive pattern but appears random instead of completely generative for the best fitness at whatever price

Hence, the design intelligence in digital fabrication is to make the best decision, but not the most optimised, out of the majority of the available sources and possibilities through digital means, in respect of multiple constrains beyond the architectural ontology. Therefore, the technique and technology are neither the purpose, nor the dominating content, but become the vehicle and one of the many ingredients that contribute to the materialisation of architectural ideas.

4 The Limitation of Digital Fabrication

Assuming that the computation in digital fabrication defines a new craft through the advanced expertise in machines instead of human hands, the persistence of ideas being shifted to computer calculation, would result in architecture becoming "super fit" and ultimately precise. However, architecture is the result of huge investment in resources and subject to natural and human forces, the fitness through digital fabrication may in fact be unfit under the real construction conditions, which inevitably include tolerance, irregularity, on-site adjustment, human error and unpredictable material deformation and land movement, "making it impractical for the physical outcome to be literally measured against its digital precursor in a presumed search for the highest level of fidelity possible" (Denari, 2012).

Therefore, most of the complex forms experiments have to remain as temporary pavilions. The recent inclusion of robots fosters the upsurge of architectural design research. However, the similar architectural concept is repeated with little effort in the architectural intelligence regardless how complex the form would be. They either spend much time and energy in studying how to program the robotic arms to achieve an easy task, or to replicate the common techniques used on the industrial production line a decade ago. These replications happen because the robotic arms empower architects' minds to complete complex forms, i.e. building arched shelters with populated cells. After all, the change of paradigm has not significantly improved the thinking ability of architectural design, or the accumulated design intelligence.

There are a few architectural researchers, such as Achim Menges, who are able to integrate design concepts and theories, and the significance (i.e. building more space with fewer materials) and aesthetic effects, with digital fabrication processes. Philip F. Yuan developed a new approach to multi-discipline resources in Tongji University, attempting to 3D print new materials for full-scale construction. He also learnt from some technological traditions like the mortise-tenon joineries in wood construction, and pottery clay production in China. The quality of synthesising the design culture with design techniques enabled the approach to achieve innovative and intelligent research outputs in digital fabrication and to open new doors for robotic architecture, rather than drifting around the fashionable forms.

5 The case of Intelligent Wave Project

In the exhibition, Robotic Future, at the 10th Shanghai Biennale, a different angle was offered on the possibilities of architectural robotics with a design-oriented fabrication approach; this was unlike other exhibitors who either keep producing another version of the complex canopy or cross the line to make real robotic machines. The goal is to make a self-supporting robotic surface based on the synthesis of abstract geometries, Self-organised Complex System Theory, 3D Print fabrication, reciprocal structural frames, and automatic control through computational protocols.

Accordingly, the design and research were conducted on the whole process, from multiple dimensions of the systems, trying to enrich the speculation of the "Robotic Future" in the field of architecture.

- Theory application

The core of the IWP is the self-organised complex system, which possesses a collection of intelligent and autonomous objects as agents that respond on the basis of local rules. Because of the non-linearity of the interactions amongst its components, the overall system behaviour is unpredictable and therefore not entirely controllable, featuring a multi-level of incidental synchronisation. "However, the system tends to self-organise, in the sense that local interactions eventually produce global coordination and synergy" (Heylighen, 2008). The self-organised complex system is neither simple nor random. Rather, it is a seemingly irregular system built on rigorous relationships, reflecting a higher order, complex but not complicated. Inside the complex system, are various subsystems that work independently within its own local boundary while corresponding to the adjacent subsystems as a whole for evolution in a larger global scale.

In IWP, the subsystems are comprised of very simple sliding rods, rotating rods and zippers. Following the geometric order, these subsystems work through their local independence and global correspondence with parts to form a self-organised complex system that presents in different forms as a whole. This process iterates, but the results will be different spatial cambers corresponding to the changes of the various local inputs. (See Fig. 4 and 5)

Fig. 4 The basic unit model

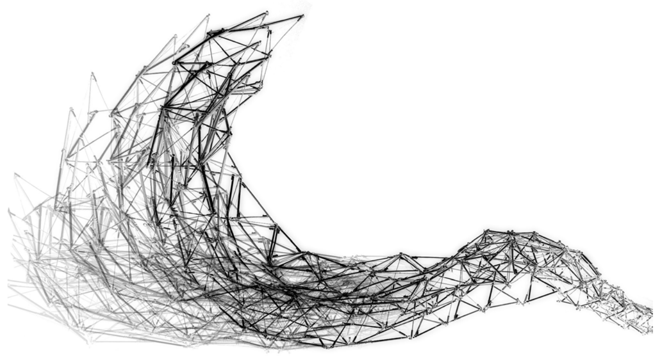

Fig. 5 The aggregation of the basic unit and its global transformation

- Formal logic – The Reciprocal Structural Frame

The repeating unit of the IWP is a triangular Reciprocal Frame (RF) structural system, which is a spatial assembly of looping linear sections without any additional supporting elements in the centre. "Such an assembly structure usually consists of simple atomic units, which are three or more rods supporting one another in closed circuits" (Nicolas Mellado, 2015). It has been studied and applied to full scale built architecture by many architects or scholars as per Fig. 6. However, all the cases that have applied RF systems, to the best knowledge of the author, have never gone beyond a static and single layered surface, which limits the geometry to be largely symmetric and remains as a canopy.

Fig. 6 the pavilion designed by Alvaro Siza and Eduardo Souto de Moura (top-left), by Chun Qing Li (top-right), by Spiro-ETH (bottom-left) and by Wang Shu and Kengo Kuma (bottom-right)

IWP consists of two layers of a reconfigurable network of triangular units and an in-between bracing of structural connection. The equilateral triangular repeating unit can be reconfigured by three synchronised sliding joints, transforming itself over a range of triangular openness in the RF structure, which can be programmed, affects its appearance and the height of the pyramidal unit (Fig. 4). The change in the size of the individual triangular units, together with the geometrical constraint of the in-between connecting braces, cause the global surface transformation of the whole structural network. The global geometrical variation adheres to the structural restrictions from the truss-like strut network. The system accomplishes a prototype that can use the same member to create non-linear camber in the free space. (Fig. 7)...../../../../010_Videos/Animation Seq Overall.swf

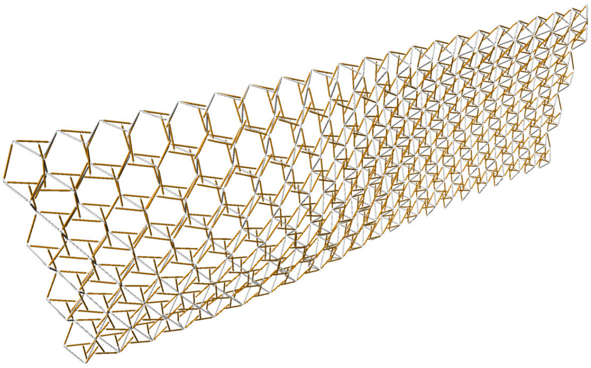

Fig. 7 Generated components populated on a free-form surface with Rhino script

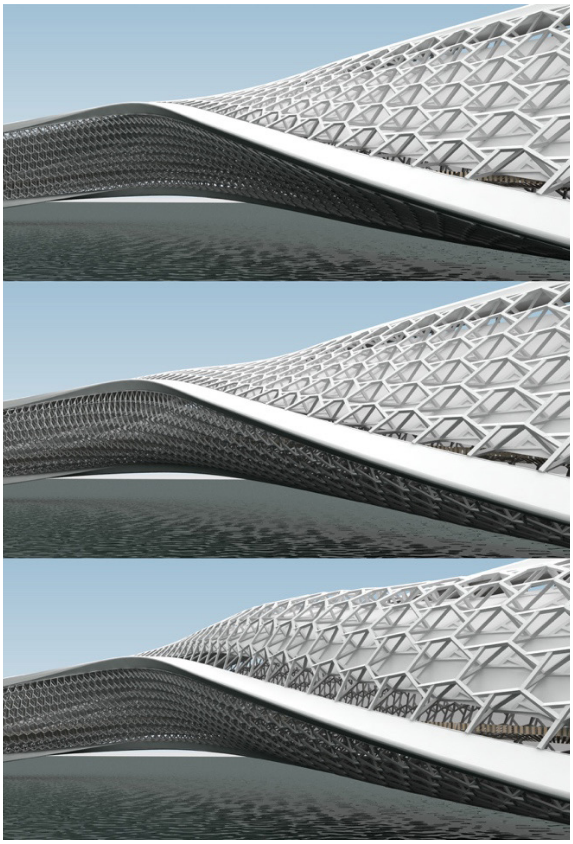

Fig. 8 Top-down method to populate the identical components to a different surface setting

The length constraint of the struts and equilateral constraint of the triangular unit is vital to the stability and computability of the system. Iterative relaxation-type optimisation is more efficient for form-finding this complex system compared to constraint-based analytical methods.

- Digital simulation

Implementation of the iterative optimisation (Pottmann et al., 2007) has been adapted to computing component population in the digital model by resembling the physical laws of the material constrains. Two computational exercises have been tested in the digital modelling processes, i.e. top-down and bottom-up method.

In the top-down method, the objective was to simulate a 3D twisted self-supporting surface with identical components (Fig. 8). Three steps of computation were implemented to achieve the population of slightly varied units (with the identical components and the differentiated sliding parameters and rotating struts). The first script generated the limit range of surface deformation, i.e. concave or convex according to the reciprocal triangles with the predefined component size (Fig. 9). The second script takes the output of the first script as graphic inputs, and populates the base layer of the pyramidal units (Fig. 10); these adapt to the surface curvature by varying the sliding joint openness. The last script reads the pyramid peak points as inputs to generate the top layer of the triangular frame with the sliding joints (Fig. 11).

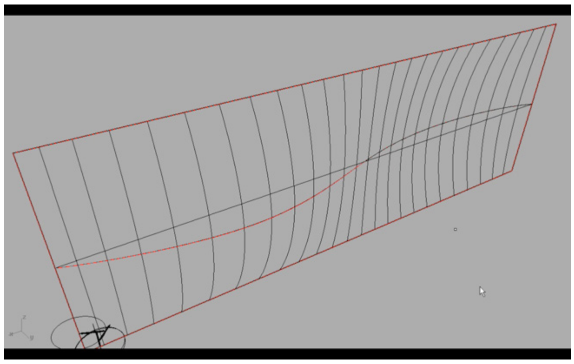

Fig. 9 the first step of computation with the generated surface deformation within the limit of predefined unit sizes

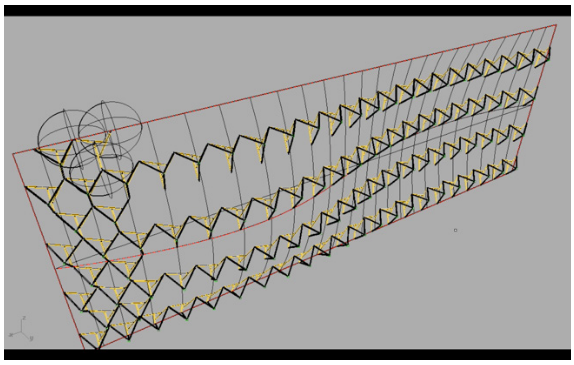

Fig. 10 the second step of computation to generate the bottom layer of the pyramid units

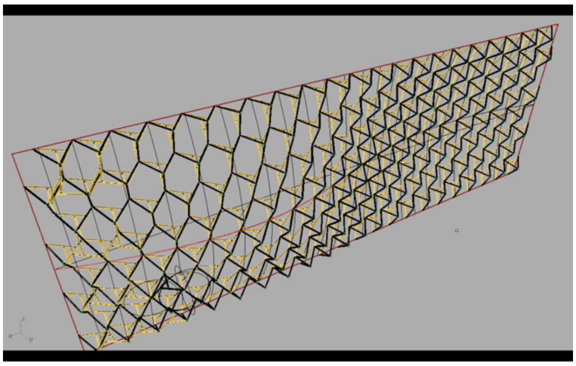

Fig. 11 the third step of computation to generate the top layer of the sliding triangle units

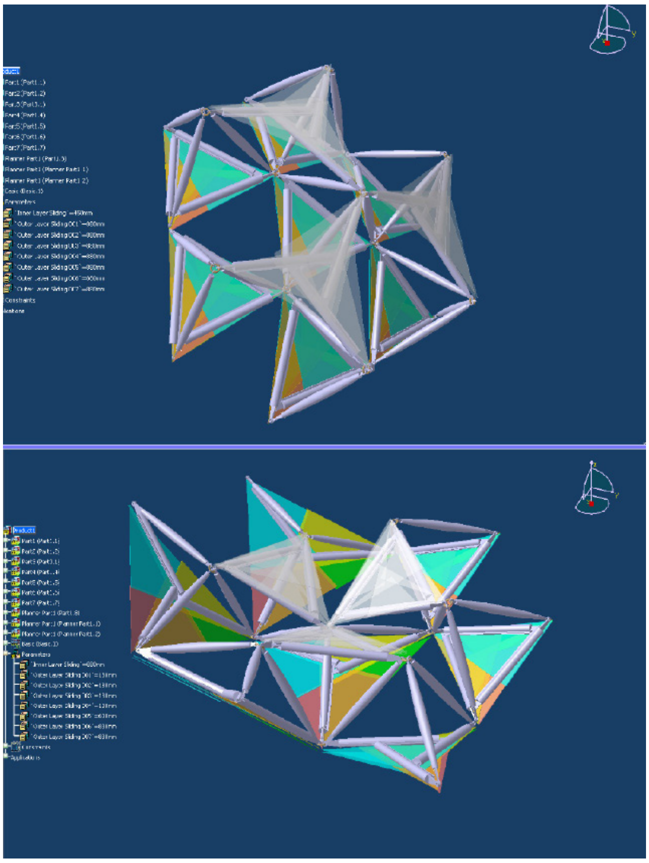

Fig. 12 The same Catia model with the geometric constrains behaving concave and convex with different parameters

Every time, the triangular frame was computed as per the iterative optimisation in order to find the acceptable position of the looping rods starting from the initial position. The advantage of this method is to visualise the global assembly for further design decisions upon the quantities of the components, but the model has to be static.

In the bottom-up method, the goal was to test the real behaviour of the material assembly with the utmost precision. We built a dynamic model with the constrain functions in Catia (Fig. 12). The process of setting up one model is a bit tedious, but once the model is created, it is possible to readily transform it by changing the parameters. This method reproduces the behaviour of the real physical assembly, but it is extremely difficult to replicate the components, with the looping constrains in Catia, when the number of units increases significantly.

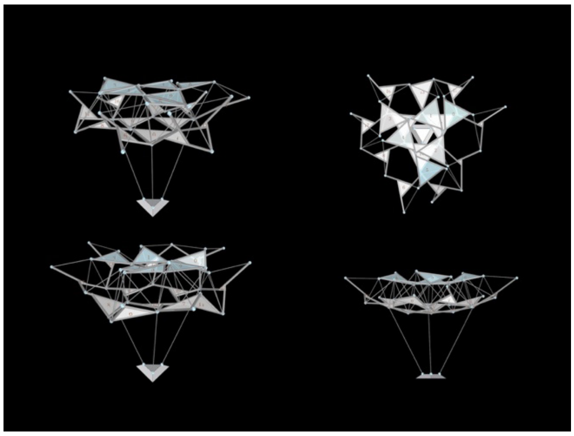

Fig. 13 The Grasshopper model for the exhibition installation

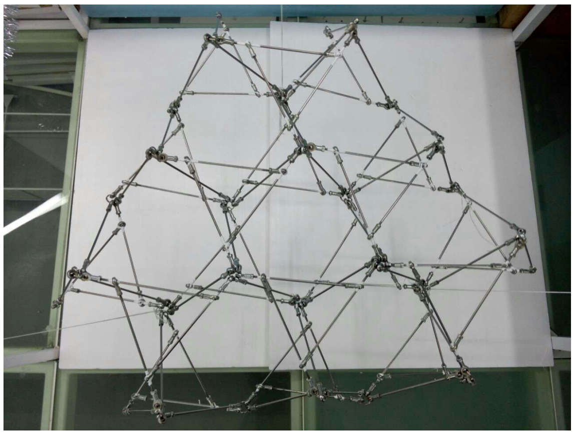

Fig. 14 The static physical testing model

Our last method of digital modelling the assembly, according to the exhibition space limit, is to apply the simulation software to mimic the physics in digital space. By wiring up the "springs" among different components and applying the vector "force", the digital assembly will deform accordingly until equilibrium is achieved. This method can repetitively compute and display different configurations under different force, but it is always an approximation of the global form and the parameters cannot be accumulated then changed (Fig. 13). Nevertheless, the resolution and precision of the digital model are good enough for us to assess the formal outcomes and guide us in making one physical model to test the geometric validity (Fig. 14) before producing our final robotic installation.

- Connection design

There are two types of connection joints between structural members. The sliding joints within the triangular unit contain an active motorised sliding linkage for changing the periphery of the unit (Fig. 15). The joints between neighbouring units and the in-between struts are passive universal rotational joints that have flexibility over a wide range of angles (Fig. 16). When the active sliding alters the size of the triangle, the rotation joints follow the motion to achieve complex global transformation. Some of the sliding joints can be made passive if the global is sufficiently constrained.

Fig. 15 The universal sliding joints

Fig. 16 The universal rotating joints

- Kinetic structure

The basic unit of the IWP is built upon the spatial triangle and the reciprocal frame system. The key is that when the pyramidal units are repeatedly connected to build a spatial lattice framed system, a series of compact structures and geometric restrictions can lead to unlimited transformations of the surface globally. The form will adhere to the structural equilibrium at any frozen moment of the transformation. The system can accomplish the "fluid form" with the kinetic structure as long as the external force is introduced to break the balance. (Fig. 17, 18)

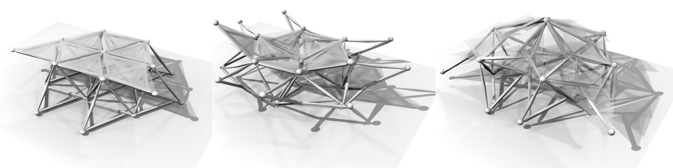

Fig. 17 The digital transformation of concave and convex caused by a sliding motion at the top and bottom layer

Fig. 18 The physical unit driven by the servo motor

- Material component

The choice of material for a 1:5 prototype of IWP reflects an efficient use of rapid prototyping techniques. Each triangular unit consists of 1-3 servo drives for actuating the sliding joint. Precise position is provided by a high-torque multi-turn servo motor driving a capstan drive with a stationary timing belt. Standard industrial components such as steel shafts and linear guide bearings are adapted for quick prototyping and rapid fabrication of the sliding joint. A number of 3D printed parts provide the housing of the mechanical components.

Apart from the innovation on the structural form and the geometric interconnection, the IWP also demonstrates new possibilities for utilising 3D printing applications on the level of the large scale components. This is quite different from the attempts to apply 3D print in the construction industry, which is still obsessed with the complex representational models for showcasing the extremely complex form. Instead, we accept the main trend building pattern that regards the construction as the combination of different materials and parts, and then builds more functional artefacts on a construction scale. Some 3D printed parts are also used in the housing of the linear guide, motor and capstan drive where the compact arrangement resulted in a difficult part for other fabrication methods. The 3D printed parts have to be designed for minimal support suitable for FDM 3D printing. 3D printed parts guarantees the accuracy while balancing production cost, ease of assembly and appearance. (Fig. 19-24)

- Control system

The control system of the IWP uses a Kangaroo[2] for form finding. The script processes a NURBS surface as global geometrical input and computes the slider position of each triangular unit. Another script uses Firefly[3], to send slider positions to an Arduino Mega microcontroller board, which relays the signals to the motors as PWM signal. This real-time control of all

---

2 Rhino Grasshopper Plugin
3 Rhino Grasshopper Plugin

motor positions allows precise timing and synchronisation of the transformation process. The Grasshopper script setup allows future implementation of other data-driven input and control. For example, using movement sensors to capture human actions and control transformation of the structure. (Fig. 25, 26)

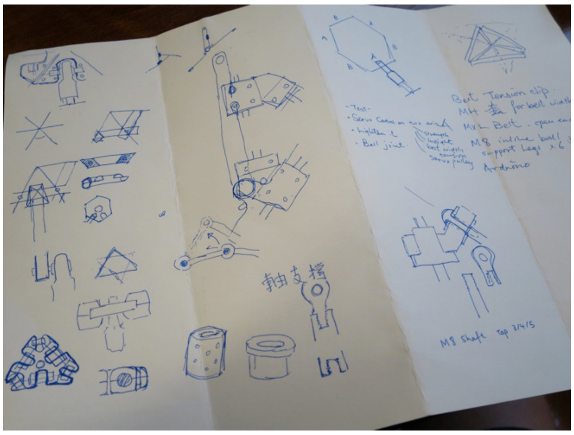

Fig. 19 Sketch of the 3d print joint design

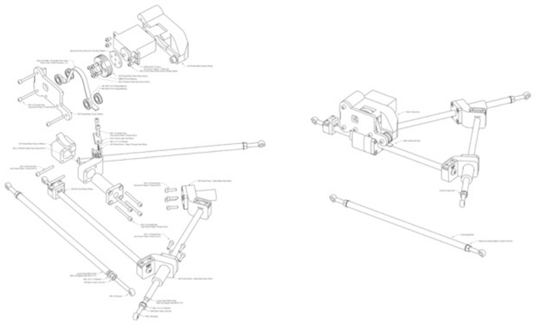

Fig. 20 Detail design of the triangular unit with sliding joint

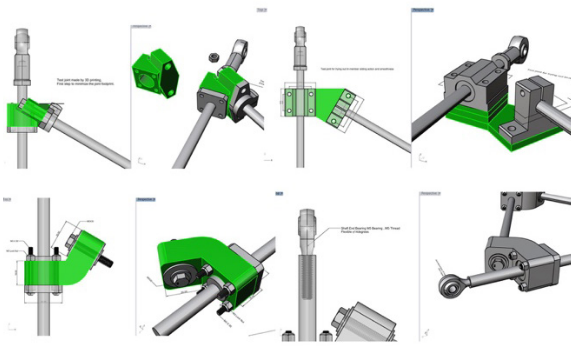

Fig. 21 Design variation of the 3D print sliding joints

- Assemble and Fix

The 1:5 prototype used 18 sliding triangles (6 on the upper layer + 12 on the lower layer). Each triangle is numbered and corresponds to the arrangements in the Grasshopper script. The 3D printing process took two weeks using one 3D printer[4], but only two days to assemble[5].

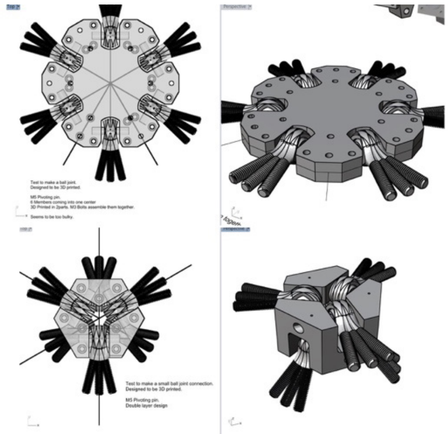

Fig. 22 Design variation of the 3D print rotation joints

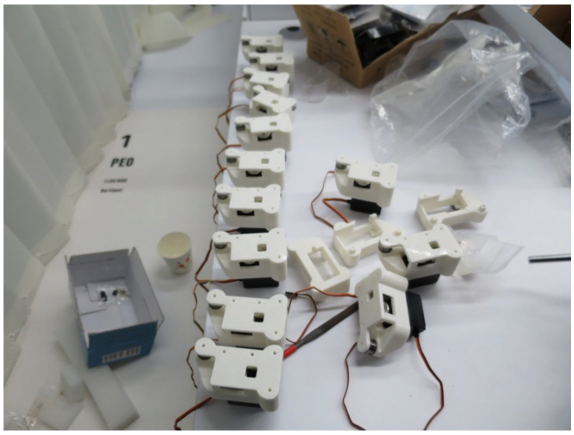

Fig. 23 3D print sliding joints

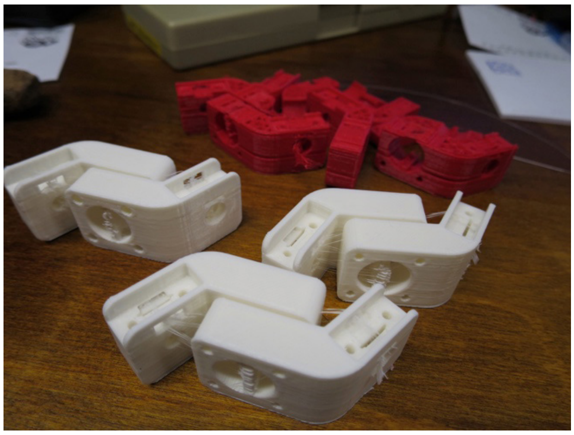

Fig. 24 3D print motor house

The prototype is fixed to a stable base using six steel rods with universal joints on both ends of the rod. The rods are a fixed length but are arranged like a Stewart platform; three connecting points on the structure are joined at the universal joint between triangles. This arrangement provided the right amount of constraints that allow the model to be ‘floated’ over the base with minimal lateral movement. Meanwhile, the movable supporting rods do not restrict the global transformation and passively follow the transformation of the lattice structure. (Fig. 27-29)

4 Makerbot Replicator 2 FDM 3D printer with PLA material.
5 A team of four students from Shenzhen University.

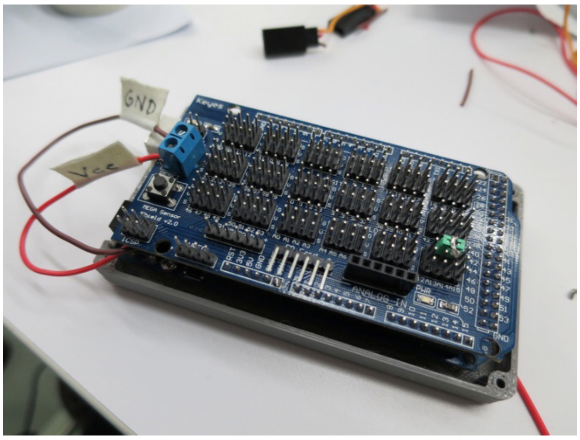

Fig. 25 Arduino Mega with PWM breakout board

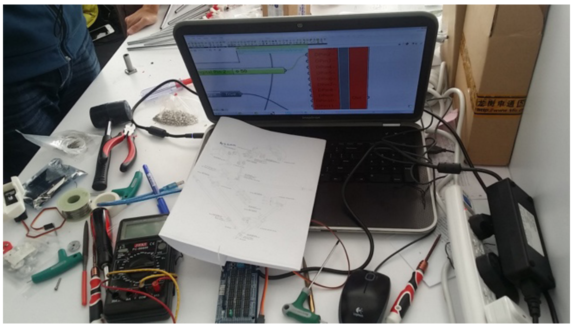

Fig. 26 Data connection test between Arduino and Grasshopper

Fig. 27 Assembly of units on the stable base

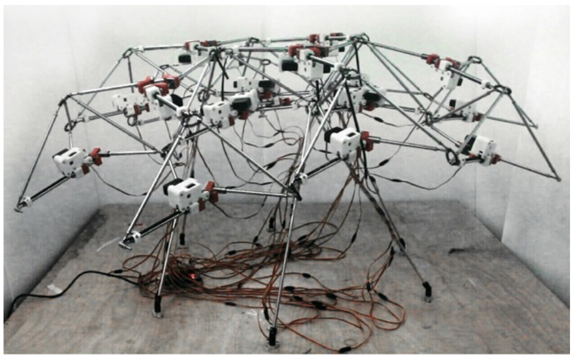

Fig. 28 The finished 1:5 model connected to Firefly control system

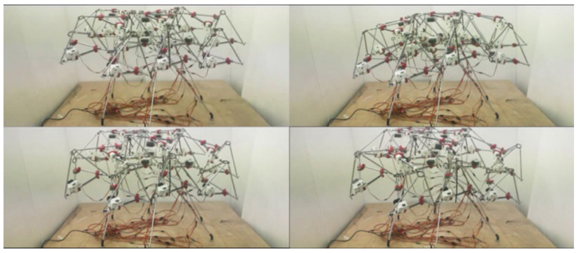

Fig. 29 Different configurations of the kinetic structure controlled through Firefly

6 Conclusion

The IWP is an experiment in robotic design and digital fabrication that encompasses a holistic design approach. It aims to fulfil an organic integration of self-organised complex system theory, system design, digital fabrication, dynamic forms, kinetic structure and programming control. Instead of blindly depending on the capability of digital fabrication tools, IWP organises resources with the available tools and materials, to realise a comprehensive outcome based on architects' expertise.

We are not the only avant-garde architects who speculate the future with the new technologies. In the history of architecture, Le Corbusier's Ville Radieuse, Metabolism in Japan and Archigram in the UK all project their imagination of the future under the huge influence of technological development and society's productivity at the time. "It reminds me of the Avant-garde architects in the 1920s that naively believed new technology could bring human beings a beautiful world, whereas the world evolved into many depressions and even the two world wars. Architects tend to be heroistic with the belief that they can save the world. Consequently, "architecture has to bear obligations to resolve all the problems which would never follow the same way as the architects wish." (Gao, 2012) An experiment could fail, and any dream of the future may vanish. We are in the wave of the digital evolution into robotics, and it is hard to make an objective and impartial evaluation of it when we are still in it. What we can do, however, is to keep an open and critical mind so that we do not lose what make us an architect while we are rolling the wave. This is also the reason why we are more interested in the research about design oriented "intelligent making" instead of production oriented machinery fabrication.

Acknowledgement

The team of the project "Intelligent Wave":

- The leaders of the design R&D: Yan Gao and Xin Guo
- The leaders of the technology R&D: Victor Leung (MIT Master of Science in Architectural Studies in Design and Computation) and Jie Ouyang (Masters student in Shenzhen University)
- Other members: Ming Zhong (undergraduate in Shenzhen University), Yongsan Huang (undergraduate in Shenzhen University) and Chuhui Cai (undergraduate in Shenzhen University)

References

Anon. (2014). Robotic Future. In: 10th Shanghai Biennale 2014 City Pavilion: Urban Work&Shop. curated by Ye Zhu, and Philip Y. Feng, organised by Shanghai Contemporary Art Museum, Shanghai, other researchers are Xin Guo, Victor Leung and Ouyang Jie.

Gao, Y., (2012). Scripted Vernacular Architecture - Invisible Computation. In: Yuan, P. F., Leach, N. (eds.) *Fabricating the Future*. Tongji University Press, Shanghai, pp. 113-120.

Johanson, B., Fox, A. Winograd, T. (2002). Inventing wellness systems for ageing in place. *IEEE Pervasive Computing*. 1(2), pp. 67-74. https://doi.org/ 10.1109/MPRV.2002.1012339

Kapadia, A., Walker, I., Green, K. E., Manganelli, J. Houayek, H., James, A. M., Kanuri, V., Mokhtar, T., Siles, I., Yanik, P. (2010). Architectural Robotics: An Interdisciplinary Course Rethinking the Machines We Live. In: 2010 IEEE International Conference on Robotics and Automation, Anchorage, AK, May 3-7, 2010 , pp. 48-53. https://doi.org/10.1109/ROBOT.2010.5509821

Lynn, G. (1988). *Possible Geometries*. Collected Essays Brussels.

Lynn, G. (2012). From Tectonics (Mechanical Attachments) to Composites (Chemical Fusion). In: Yuan, P. F., Leach, N. (eds.) *Fabricating the Future*. Tongji University Press, Shanghai, p. 21.

Menges, A. (2012). Future Wood: Material Integration in Computational Design. In: Yuan, P. F., Leach, N. (eds.) *Fabricating the Future*. Tongji University Press, Shanghai, pp. 42-49.

Mitchell, W.J. (2000). *e-topia*. Cambridge, MIT, MA.

Pottmann, H., Asperl, A., Hofer, M., Kilian, A. (2007). *Architectural Geometry*. Bentley Institute Press

Streitz, N., Geissler, J., Holmer, T. (1998). Roomware for cooperative buildings: Integrated design of architectural spaces and information spaces. in cooperative buildings - integrating information, organization and architecture. In: Proc. CoBuild '98, Darmstadt, Germany, 1998, pp. 4-21.

Van Berkel, B. (2012). Understanding the Real Values of New Materials and New Digital Techniques, Fabricating The Future. In: Yuan, P. F., Leach, N. (eds.) *Fabricating the Future*. Tongji University Press, pp. 153-160.

Walker, I. D. (2001). Issues in Creating 'Invertebrate' Robots. In: Proc. Adaptive Manipulation with Animals and Machines, 2001, pp.1-6.