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Abstract

This paper describes the abilities of parametric iterative design with collaboration of robotic fabrication workflow in structural optimization of the nodes (joints) of special grid-based structure. Experimental structure built in robotic fabrication workshop – (the Dynamo-BUILD workshop at the 2016 International Conference on Robotic Fabrication in Architecture, Art, and Design Conference in Sydney, Australia) - is taken as a case study. In this study, the complexity of structure form combined of joints and members is resolved and developed through parametric design algorithms. Focusing on joints, the case gives workflow structure methods of design and fabrication that transfer the level of mass simplicity production to iterative complexity production .Furthermore, these methods also respect the manufacturing processes and material properties of nodes. The structure was fabricated using robotic fabrication techniques after design optimization using parametric computationally driven manufacturing processes. In order to move from the computational design environment to joint fabrication, custom robotically process was developed to assemble making full structure series of nodes which saved time; cost; and exerted effort if compared to the traditional mass production processes.

Keywords

Robotic fabrication. Parametric Optimizations. Computational design. Joinery structure. Algorithms

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ABSTRACT

This paper describes the abilities of parametric iterative design with collaboration of robotic fabrication workflow in structural optimization of the nodes (joints) of special grid-based structure. Experimental structure built in robotic fabrication workshop – (the Dynamo-BUILD workshop at the 2016 International Conference on Robotic Fabrication in Architecture, Art, and Design Conference in Sydney, Australia) - is taken as a case study. In this study, the complexity of structure form combined of joints and members is resolved and developed through parametric design algorithms. Focusing on joints, the case gives workflow structure methods of design and fabrication that transfer the level of mass simplicity production to iterative complexity production .Furthermore, these methods also respect the manufacturing processes and material properties of nodes. The structure was fabricated using robotic fabrication techniques after design optimization using parametric computationally driven manufacturing processes. In order to move from the computational design environment to joint fabrication, custom robotically process was developed to assemble making full structure series of nodes which saved time; cost; and exerted effort if compared to the traditional mass production processes.

KEYWORDS

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1. INTRODUCTION

Formal complexity often has implications for structural typology and conversely structural typology impacts formal complexity (Tomlow 1989). In many cases, formal complexity results in custom components that exhibit a high level of functional complexity (Fagerstrom et al 2014). Grid-based structure typologies are rapidly developed from simplicity and regularity to complexity and irregularity (Fig.01). Regular grid-base long spans structure - are typically composed of nodes and members, which have to be identical in shape; size and dimension. Traditionally, they were manufactured through mass production method, where the structure is formed by identical elements. However and in case of elements dissimilarity of contemporary design typology, the traditional method of fabrication had limitations and was inefficient and in turn was inapplicable in the construction field .This was due to the fact that the structure elements were diverse and no longer identical. Parametric computational design in collaboration with industrial robotic fabrication tools have eliminated many of the design restrictions in order to construct free form Grid-based structure - such as grid shell, truss, space truss, and membrane (Fig.02), this free form has to go through a workflow of four successive phases: members and joints structural analysis ; parametric design optimization for members and joints ;preparation for the fabrication and finally small scale fabrication testing . The workflow has to be in an appropriate software environment so as to create integration between these four previous mentioned phases.

This paper aims at study the method of nodes design and fabrication in special structure forms to reach the optimum algorithmic workflow recommended for the designing and manufacturing

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process.in order to achieve such an aim, the research methodology starts with reviewing three contemporary experimental workshops - chronologically ordered – to understand the development of design techniques through studying design and fabrication challenges, limitations and possibilities in each case. Next, it studies the stat – of – Art of each workshop and listing the optimization design factors. Finally, it highlights the recent workshop which is taken as a case study to test the design-fabrication collaborative workflow in details. Within this case, an application has been done on joinery design construction, testing the optimization design and robotic fabrication factors.

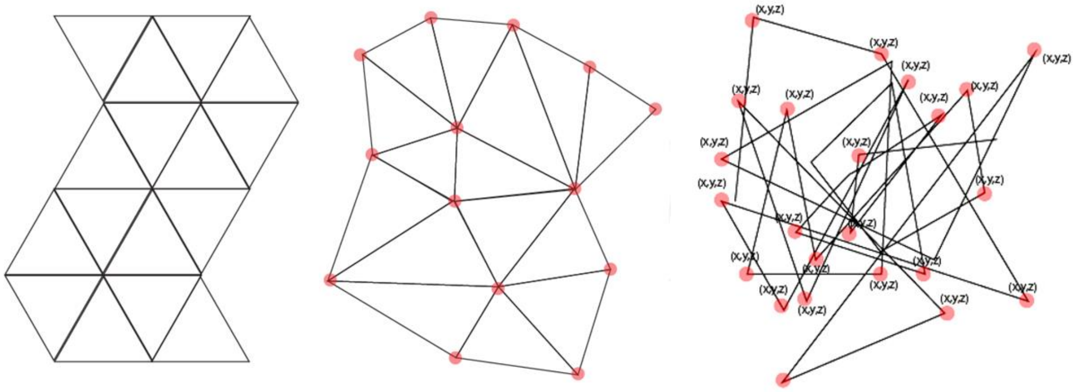

Fig.01 Regular-simple grids need identical joins while more complex and irregular grids needs dissimilar optimized series of joints; reference: the author

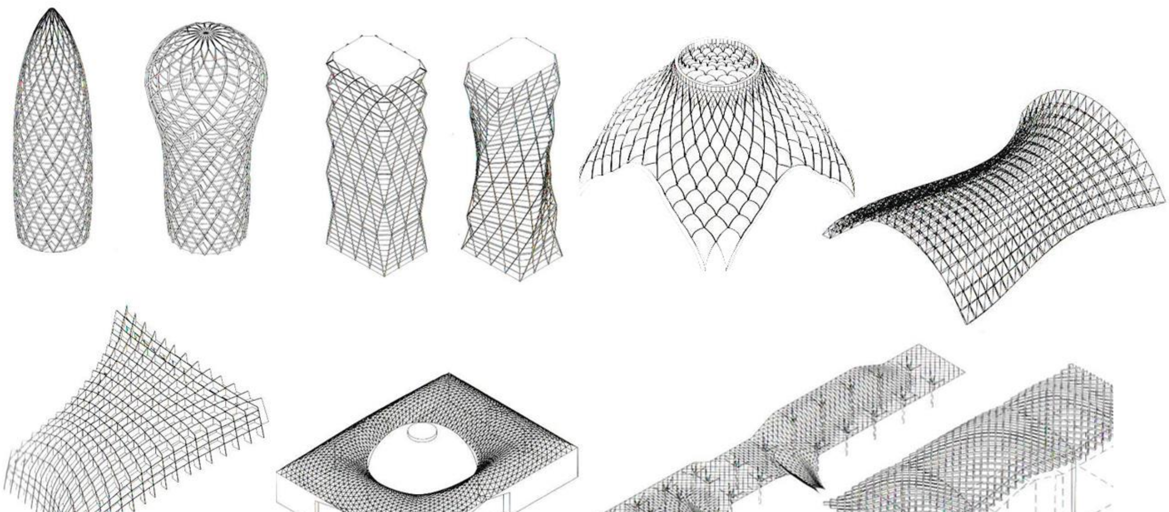

Fig.02 Contemporary grid-based structure typologies that have been constructed using joinery parametric computational design optimization and fabrication; reference: -Farshid M. (2009) "The Function of Form, page 156 and 342

2. JOINERY DESIGN REVIEW

Joinery optimization design is developed not only through the industrial applications, but also through many contemporary problem/solving experimental researches on digital-fabrication and robotic workshops. Recently, researchers integrate between academia and industry in order to test

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the joinery construction in real life. The experiments feedback helps researchers to develop the workflow and the operation of joinery design and fabrication. The following applications are ordered by time of application in order to test the technology development of designing joints.

2.1 ICD/ITKE Research Pavilion, 2011

In the case of the Research Pavilion application (Magna R et al 2013) - done by ICD/ITKE in Stuttgart University - a folded-plate structure built from plywood and cross-laminated timber panels (CLT) as a prototype of fabrication technique. "The construction requires curved line CLT joints, which are difficult to address with state- of – art jointing techniques for CLT. Inspiring by traditional woodworking joinery, we have designed connections for the integrated attachment of curved CLT panels (as shown in Fig.03), utilizing digital geometry processing tools to combine the advantages of traditional joinery techniques with those of modern automation technology" (as shown in Fig.04) (Christopher R.).

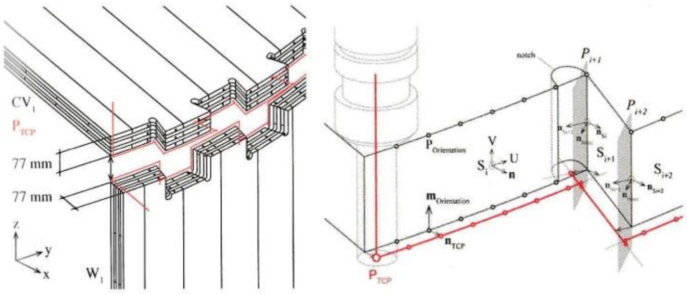
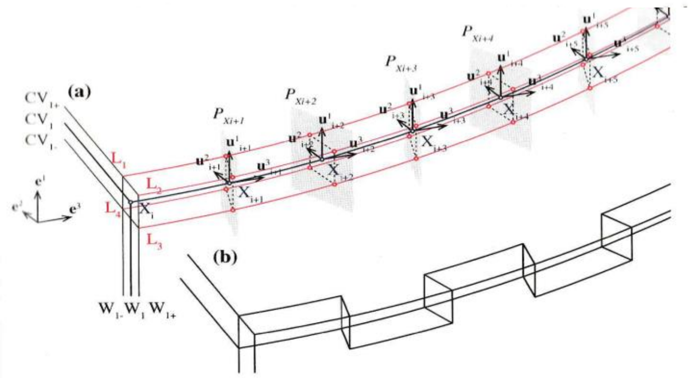


Fig.03 Generation of the dovetail-type joint geometry through intersection of a set of planes Pxi with the four curves L1 , L2 , L3 and L4 . a CV1 is the part , the + and – show the intersection layers and W1 is the part ,the + and – show the intersection layers b it is the same parts once jointed. Part CV1 above and part W1 below



Dovetail-type connections W1 – CV1 and CV2 and W2 on the full-scale prototype. this schematic drawing showing the CLT panels and joints including layers and stress cuts, Right principle of machine code generation on a curved joint, using parametric surface evaluation Reference: Page 71, Robotic Fabrication in Architecture, Art and Design 2014

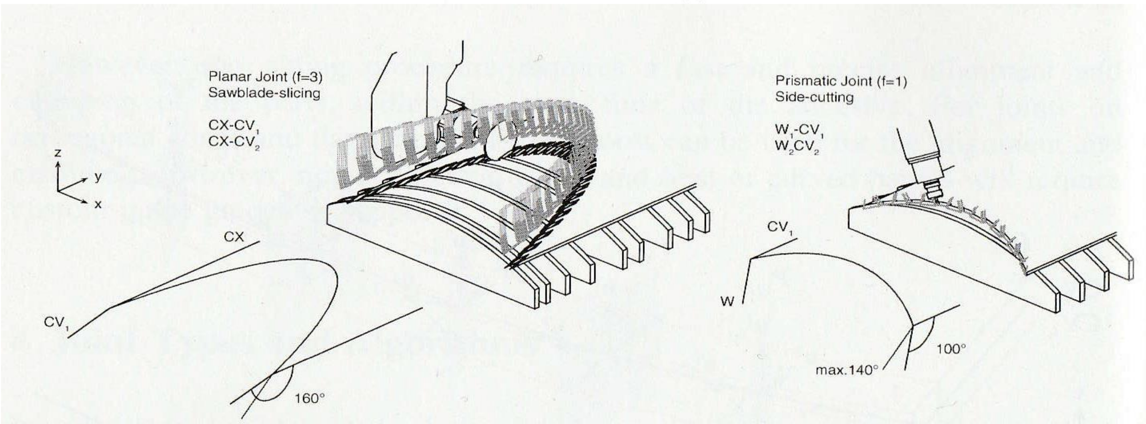


Fig.04 Joint fabrication (tool path plot). Left planar "finger joint-type "connection (connections CV -CX), Right prismatic "dovetail-type" joint (connections W-CV). Cut the open slots of these joints, we used a saw blade-slicing technique instead (fig06, left side), making multiple vertical cuts for each slot. This method allows us to fabricate very obtuse folds on simple, non-cantilevering supports. Reference: Page 72, Robotic Fabrication in Architecture, Art and Design 201

2.2 Advanced Timber Space-Frame Structure, ETH Zurich, 2013

A prototype of Timber Space- Frame was built by integrated topology optimization and fabrication done in research collaboration between ETH Zurich and Aarhus School of Architecture. The problem /solving and optimizing of joints have been demonstrated in this advanced research under the development of Robotic Architectural fabrication and parametric design environment. Through the across-application workflow, a direct optimization chaining and robotic fabrication are developed, in which the parametric data is driving subsequent processes managing the timber joint intersections, controlling robotically member prefabrication, and spatial robotic assembly of the optimized timber structures(as shown in Fig.05) . The joints created rationally according to the timber member cross-section dimensions included in the joint:" joints containing members of only one dimension type are trimmed against a shared plane derived from the bi-sector of the center axis of the intersecting members. For every insertion operation, a connectivity check is performed at the end-node of each inserted bar member (opposite of the joint node). If found, the connecting bar will be inserted ensuring, where possible, a build-up through triangulation, which help to ensure physical stability during assembly". (Asbjorn S, and Oded A 2016)

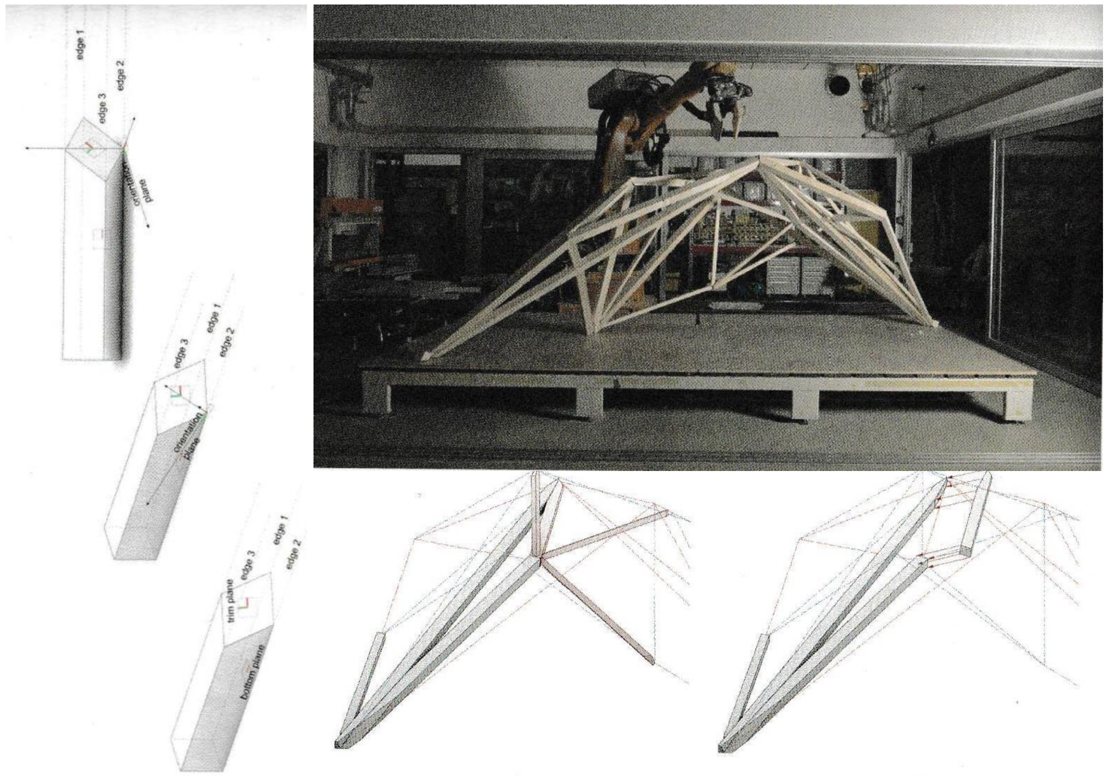


Fig.05 The prototypical structure (Michael Lyrenmann). Assembly sequence example. From the list of possible node connection (left), the inserted member is selected based on connectivity and priority level, and insertion trajectory computed from the node geometry (right) with the joints diagonal cutting orientation. Reference: Page 197, Robotic Fabrication in Architecture, Art and Design 2016

2.3 Lo-Fab Pavilion, 2015

In 2014, Lo-Fab Pavilion was created by MASS Design Group for Design Research (CDR) at Virginia Tech. For this case, individualized special steel nodes were fabricated, each having four custom tabs and a single uniform element—a central cylinder—that provided registration for robotic tooling and welded assembly, Individualized struts were uniform in section but varied in length. Each strut had a custom dado in either end to receive the steel tabs from the welded assembly (as shown in Fig.06 and Fig.07)

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"The structure was fabricated using state-of-the art collaborative robotic fabrication techniques and a combination of traditional craftsmanship and computationally driven manufacturing processes. The team worked in collaboration with Autodesk to develop a novel design-to-robotic fabrication workflow using the emerging visual scripting interface Dynamo. A custom robotically assisted welding process was developed to assemble 1880 steel parts making up 376 nodes that saved over three weeks of labor when compared to traditional processes". (Nathan K 2016)

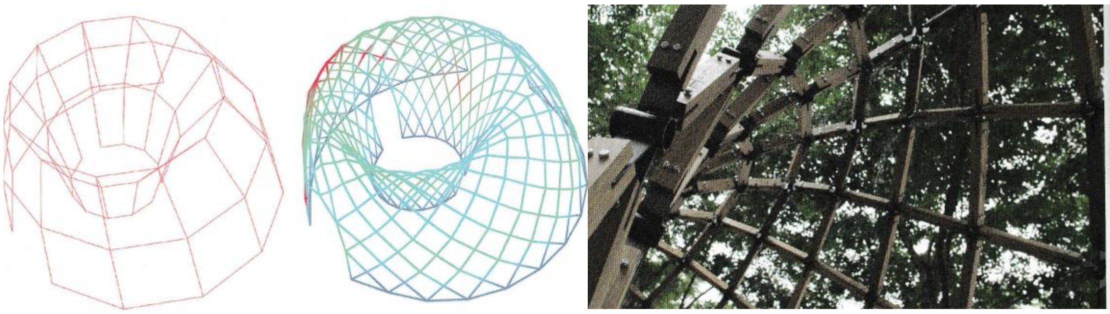

Fig.06 MASS Lo-Fab Pavilion installed in Boston for the Biennial 2015. (On the Fig.00 right) mesh topology used as input to Grasshopper model .Right real-time visual feedback from Grasshopper, showing discretization and Finite Element analysis the rainbow gradient indicates surface deflection where blue is 0" and red is 0.75" Reference: Page 364, Robotic Fabrication in Architecture, 2016

Fig.07 Photograph and diagram showing the Joints labelling system used to guide all manual fabrication and assembly Photographed by Virginia Tech Center for Design Research. Reference: Page 369, Robotic Fabrication in Architecture, 2016

2.4 Experimental review guidelines

The guidelines of reviewing the above mentioned experimental workshops illuminate the developments done for designing and fabricating of joints as follow:

In the first case - ICD/ITKE Pavilion, 2011- the challenge found in this pavilion was the second curvature of the total form that affects the joints position and shape. The solution for this challenge was not creating a separate plane joints but a connected joints on the edge of the curvature surface that – parametrically optimized – had the same partial curvature with accurate values in each joint position. The main guideline for this case is to take the whole form surface curvature values into consideration in designing optimization process.

In the second case- Space-Frame Structure done by ETH Zurich 2013- the main challenge was the ability to have the accurate cutting angles for joints from all different directions referring to the joint centroid. This helped to correctly connect the timber members together. The solution was to get the common intersection of members' orientation. After that, the intersection node provided the normal vector for each direction of members in order to get the perpendicular plane surfaces of these vectors. By having a final intersection between these surface planes and each member, the accurate cutting angel was defined. the main guideline in this case is to involve members vector directions and the intersection angels inside the workflow as main data of joint optimization process, but the final joints have also been not separated.

In the third case - Lo-Fab Pavilion 2015- the Stat- Of – Art in this case is making separate joints, which are identical in central shape, but different in outer tab connection angles with each member. In order to do this, the data extracted by member orientations – especially central vector directions – had been duplicated to be used for joint tabs formation. The main guideline in this case is the duplication of all geometrical data of members from both sides that creates corresponding joint tabs tagged with reference serial number. The taps entered inside the member in correct angel, while the center of joint was separated from the member.

Though the previous experiments have been successfully handling joinery design and fabrication, the idea of entering the tip member inside the joint has been ignored because of the limitations of working on such a method as each joint can have many random holes with different angles that may cause clashes in final assembly.

3. DYNAMO BUILD WORKSHOP CASE

The Dynamo-BUILD workshop at the 2016 International Conference on Robotic Fabrication in Architecture, Art, and Design Conference in Sydney, Australia, is taken as a case study of joinery design; optimization; fabrication assembly . all previuse guidelines were taken as basics during the workflow process. This case describes the project-based development of the grid-based structure starting from the conception phase; passing through parametric design optimization of nodes and members; to robotic fabrication and finally site assembly. The study also focuses on the contemporary collaborative robotic fabrication environment and Dynamo-based robot motion control plugin, which were developed as part of this workshop project

3.1 Parametric design optimization

The Grid-based geometry is generated by an algorithm, which divides the final form into nodes and struts. Structure is formed - using Dynamo software as parametric design environment - in order to control the final structure grid-based parts. Hence, the basic conditions of this geometrical part are unique, the bending moments internal forces inside the members are unbalanced .The joints fastening the members have to be designed and optimized to keep members in tension and compression balance. The joints of the extracted form are different in connection positions with members .Theses connections have to be so far optimized in its accurate position on the joints and member entering angles. One more advantage of this optimization is to avoid the clash among the members when entering inside the joints .The final output of this process is a list of joint indices. Each joint among this list is labeled with the exact position of the members with their accurate angles (as shown as Fig. 08).

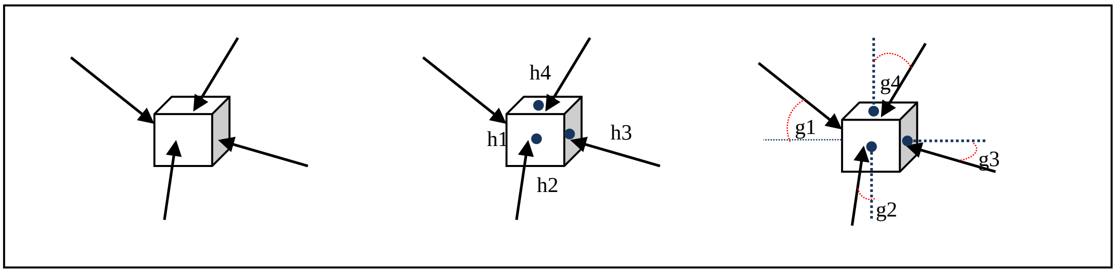

Fig.08 data extracted to fabrication is the exact holes positions and their accurate angles. Arrows show the members vectors, h represents the hole position, g represent the entering angle. Reference: the author

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3.2 Preparing joints for fabrication

The developed design system helps to provide all the construction data for each individual part of the structure. The algorithm detects automatically each joint and adds notes on it. These notes are a series of holes, which were custom prepared to robotic fabrication and attached with a reference index number. The corresponding data was organized through a CSV file that extracts a linked-based data sheet to robotic software environment. While the structure numbers were also labeled by related indices-followed by the members' length- all joint data sheets contain all the manufacturing and assembly data needed to complete the structure. The final output nodes file will help users to manage each individual joint data, these data are as follows:

1- The joint serial number that represents its position on the whole structure.
2- A number of perforation will be created inside the joints
3- Accurate perforation positions labeled by a serial number
4- Members' serial positions on the joint that match with related perforations
5- The angle of entering the joints inside the perforation

3.3 Robotic Joints Fabrication

In order to facilitate the fabrication operation, managed by robot, an ABB IRB robot collaborative work has been developed and positioned above the work surface ,where a vertical drill is fixed to be used later on to create the joints` holes. Each cubic joint is manually fixed on the robot –tip. The robot starts reading the joints` data : joint serial number ,perforation co-ordinates ,dimensions and angles .In the next step ,the robot moves the joints towards the vertical drill using its six axes .Then the robot justifies the accurate position of the joints so as the fixed drill starts to make the required joint holes . After finishing this operation, the joint is isolated from the robot tip as it returns back to the starting position (as shown as Fig. 09). This operation is repeated to create the whole joints holes required for the structure. During the operation, the robot arm is completely separated from the user to enable safe collaborative interaction.

Fig.09 The Robotic Joints Fabrication: (Right) the starting point of the robot after manual fixation of joint on its tip, (left) the robot while fabrication after reading the joint data Reference: Photographed by the author March 2016 at Dynamo-Build Workshop, Sydney

3.4 Joints Assembly

After fabrication, all joints are packaged in groups , based on their related index position on the whole structure. Onsite, these packages are organized according to tag-labels attached with the responding indices of the structure's members for use during assembly. The sequence of assembly has been launched to maintain the structure that has been continuously built by moving from the base to the top of the structure from both sides (as shown in Fig.10). This strategy allows connecting lower base horizontal members to the corresponding joints, and then connects the upper vertical and radial members for concentric assembly without the need of outer supports. These connections provide zero tolerance between the joints and wooden members. Even though, few manual interventions have been done on site to resolve some variations to fix some trivial deviations among the structure parts.

Fig.10 The prototypical structure assembly after the Assembly of joints from the base to the top of construction from both structure sides. Reference: Photographed by the author March 2016 at Dynamo-Build Workshop, Sydney

4. CONCLUSIONS

Parametric design optimization in collaboration with robotic fabrication is enabled to increase the manufacturing ability of special structure that formed of dissimilar series of joints and members. One of the main advantages of this collaboration is the importance of realizing the innovation in architectural forms and enhances their construction methods.

The parametric- robotic collaborative techniques used for the joinery make use of the computational fabrication technology for creating the joints and utilizing digital geometry processing tools .As a result, the geometry and the robotic machining code have been generated. The need to merge between the design practice in the context of applied academic research and the industrial technology creates new opportunities for architectural design innovation especially in the construction of modern structural forms.

The approach of integrated performance between the robot and the parametric design environment has been successful in the design optimization of joints. The Dynamo-BUILD Workshop Case - after the fabrication operation - has produced 276 custom joints and 620 diverse members. This fact indicates that the dynamo software -to-robotic fabrication workflow based Kinematic simulation is a recommended parametric software tool to create structure optimization and to facilitate the iterative mass production of complex dissimilar joinery of grid-based structure forms.

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This study is considered to be one of the basic platforms for advanced research in robotic fabrication, parametric design optimization for structure purposes, and the development of computational workflows. Furthermore, it is a step forward towards automation of the construction of complex architectural forms. It has also explained a new method of merging Design Robotic automation strategies together with architecture and construction applications.

It is quite clear that this case study is mainly about optimizing the joints design and manufacturing. However, it also indirectly provokes many ideas and concepts that would in turn be future studies to more enhance such optimization process. This is due to the fact that there are some factors that have not been taken into consideration in this case study , such as using different materials when creating the joints and not being restricted to one material , which has been the wood in this case study .please find below some recommended and suggested ideas that might help in developing and improving the design and manufacturing of joints in the future from all different aspects: •Changing the connections type and shape • Changing the connections material •Clash detection of different members inside the joints •Increasing the joints resistance so as to avoid the friction between the joint and the members entering this same joint

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