Robotic Fabrication of Non-Standard Material

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ABSTRACT

This paper illustrates a fabrication methodology through which the inherent form of large non-linear timber components was exploited in the Wood Chip Barn project by the students of Design + Make at the Architectural Association's Hooke Park campus. Twenty distinct Y-shaped forks are employed with minimal machining in the construction of a structural truss for the building. Through this workflow, low-value branched sections of trees are transformed into complex and valuable building components using non-standard technologies. Computational techniques, including parametric algorithms and robotic fabrication methods, were used for execution of the project. The paper addresses the various challenges encountered while processing irregular material, as well as limitations of the robotic tools. Custom algorithms, codes, and post-processors were developed and integrated with existing software packages to compensate for drawbacks of industrial and parametric platforms. The project demonstrates and proves a new methodology for working with complex, large geometries which still results in a low cost, time- and quality-efficient process.

1 Wood Chip Barn's Truss.

INTRODUCTION

Timber forks as a material

Commonly used for structural building components, wood is typically treated as a rectilinear material—its natural forms reduced to square sawn timber and various sheet materials. While producing complex forms, recent production of doubly curved glulaminated timber components furthers this treatment. Without consideration of their internal fibres, logs are sawn to regular dimensions by manufacturers for ease of processing; in the process, wood's internal fibers are cut, thus sacrificing strength (Carpo 2011, 105). A wasteful redundancy becomes apparent, in which material is processed two or more times to achieve characteristics that may already be present in the original material. Analogous to the intuitive assembly of specifically curved timbers in traditional ship building, alternative conceptions of design and fabrication processes have recently been proposed (Monier et al. 2013; Stanton 2010) that address this redundancy. The intention of using timber in its natural form is to harness the strength of its continuous grain—chains of cells that are optimally aligned to transmit force (Desch and Dinwoodie 1996). New non-standard technologies address the conventional reasons for avoiding timber in its natural shape and form in the construction industry; complexity in handling, processing data, and difficulties encountered during the fabrication process. The project began with the a need to understand a 'good fork.' Slater and Ennos showed that tree forks become stronger with increase in inclination away from the vertical axis, which leads to the formation of more elliptical branches in cross-section (Buckley, Slater, and Ennos 2015). This principle promoted exploitation of this embedded strength in its inherent form. With this as a guide, a number of potential structural systems were developed based on the fork's Y-shaped geometry. In the built work, 20 forks are used to achieve a Vierendeel truss-like structure spanning 25 meters without the need for customized steel sections.

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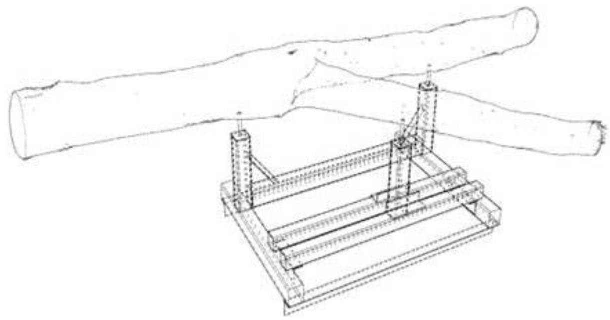
2, 3, and 4 Robotic Milling.

Within this paper, four key explorations are elaborated: the development of a precise geometric referencing system to ensure consistent placement of each component, independent of its irregular surface features; simplifying the information acquired from photogrammetric 3D scan models; development of geometries which are independent of inaccuracies caused by scanning techniques; and analysis of existing software solutions and development of milling strategies and robotic toolpath generation.

GEOMETRIC REFERENCE SYSTEM

Working with a complex and irregular material, an important consideration throughout the project was ensuring the precise handling of the forks. The whole fabrication workflow was organised around a consistent referencing system to ensure a precise translation of data between digital and physical environments. This referencing system consisted of three points that were physically drilled in to each fork component—defining a local origin point, orientation axis, and plane analogous to a local construction plane in 3D-modelling software. These holes were picked up in the 3D-scanning process so that they could be incorporated in the digital modelling processes and ultimately transferred back to the physical realm by being used as the supporting points when the fork component was mounted on a 3-point jig which is pre-calibrated by the robot inside the robot cell.



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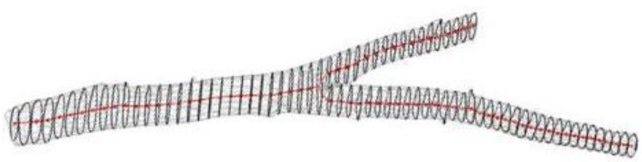

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5 Diagram of a fork with 3 points/pins, trolley, rail.

6 Extraction of centre-line.

7 Fabricated geometries: Truncated cone shaped tenon and mortise.

SIMPLIFIED INFORMATION

The photogrammetric method, one of most cost-effective solutions to extract 3D models from 2D imagery, was used for the scanning of the forks. The main constraint of working with this method, which used Autodesk's 123D Catch software, was the inaccuracy in the acquired measurements (Erickson, Bauer, and Hayes 2013). From the data collected by scanning 24 forks, an average error from +/-3 mm to +/-15 mm was found. Another drawback in using the photogrammetric method was that the forks scanned could be extracted only in the form of polygonal meshes, which increased the processing and computational time, especially when each fork geometry is represented by a mesh with an average of 60,000 planar faces. Hence the information was required to be reduced to minimum without compromising on the obtained accuracy.

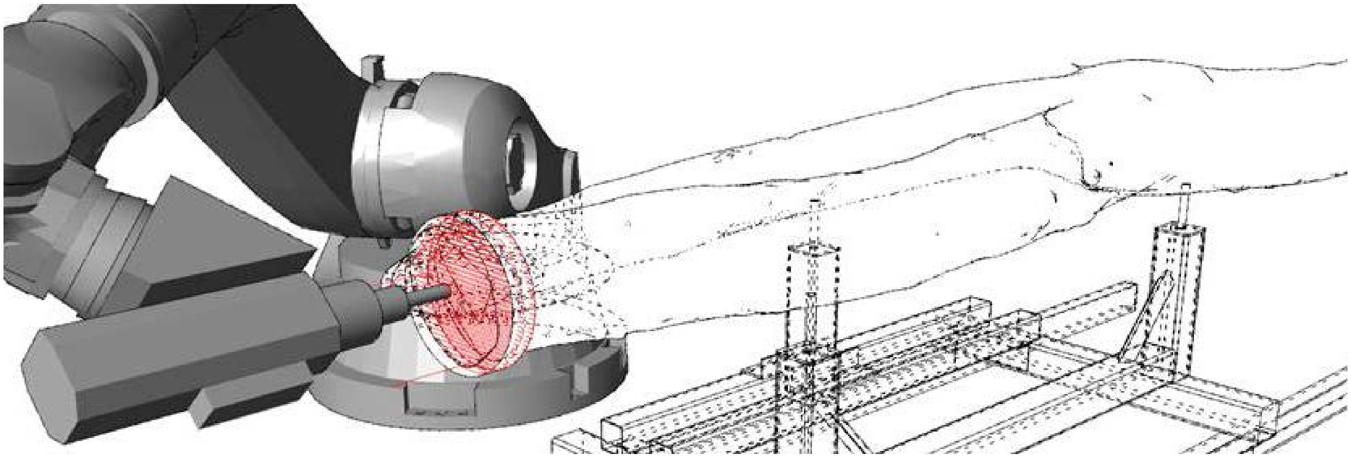
Traditional timber-framing methods include the projection of straight centrelines and axes onto irregular pieces of wood. Measurements are then taken outwards from this arbitrarily introduced centre geometry to ensure that variations in the tree's form have no bearing on the overall organization. For this project, rather than straight centerlines, centre curves are defined using a polygon-based method. Transverse sections are cut through each fork at regular intervals to obtain the outer profile of their geometry and then local best-fit diameters and centroids are calculated for each profiles' section, which are then interpolated to generate the medial curves. Points and vectors could then be extracted from the centreline throughout the entire geometry of the fork, which was essential for the development of geometries to be fabricated.

DEVELOPMENT OF FABRICATION GEOMETRIES

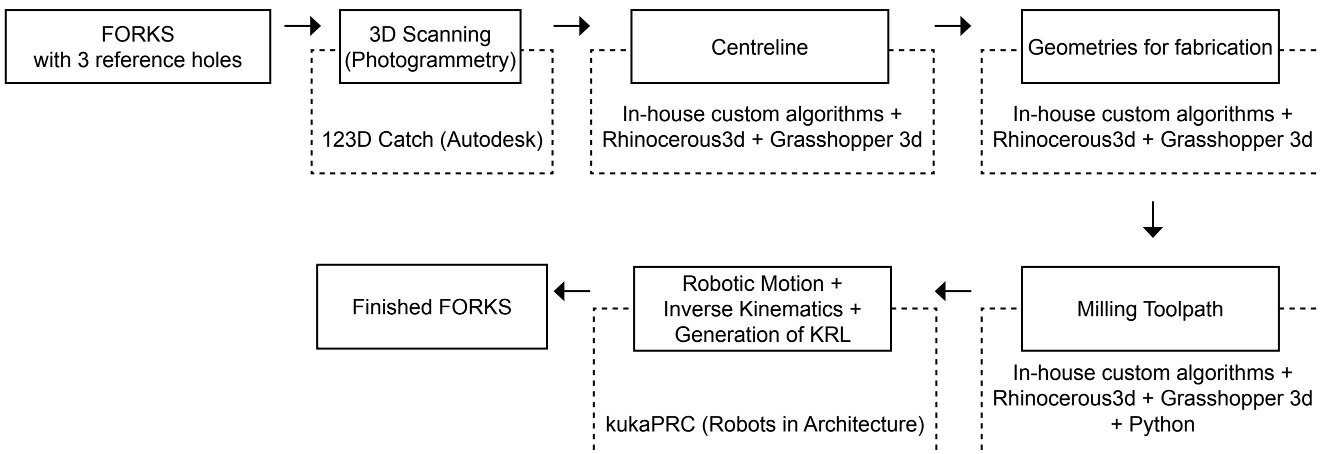
Due to the inaccuracies of the 3D-scanned fork mesh, all geometries to be fabricated were developed with respect to the three-point reference system and centrelines. Therefore, on a global scale, the geometric connections of one fork will match with the geometric connections of another, though the fabricated geometries of a fork might not have been at a precise location with reference to its own scanned mesh volumes. Also, two more important precautions were taken while developing the geometries. First, an average thickness of 15 mm was added to the external surfaces of all geometries to avoid damaging the milling cutter when the scanned geometry was smaller than the actual physical size of the fork. While this process saved the cutter from damage, it caused unnecessary air milling where the physical material is less than the size of the digital geometry. Secondly, for situations when the scanned geometry was larger than the actual size of the fork, all finishing or inner surface geometries were deeper offset by 15 mm, which resulted in subtracting more material than required.

USER-INTERFACE

Recent developments in architectural programming interfaces for computational design and fabrication, especially in Rhinoceros3D and Grasshopper software, have allowed the user to graphically code and observe real-time results as the code develops. No ready-made plugin was available off the shelf for providing milling strategies for a given geometry. This parametric interface was an undeniable necessity where repetitive fabrication methods were required to be applied on 20 forks which were considerably



8 Robotic Simulation using in-house algorithms, Kuka-PRC in Grasshopper3d and Rhinoceros3d platform.



9 Work-flow of the fabrication process.

different in shape, size, and form. The kukaPRC plugin provided an inverse kinematic (IK) solution within the Rhinoceros-Grasshopper interface, which allowed checking and prediction of the problems encountered during the robotic simulation. The challenge using this IK solver was that the predicted robotic simulation errors could not be automatically rectified. Industrial software packages—like Mastercam/Robotmater—were taken into consideration, and which offered highly competent milling strategies and had the capability to tackle the problems stated, but lacked flexibility and were limited in the transferring, handling, development, and manipulation of irregular geometry. Hence, the main aim was to develop a single platform for all specified tasks.

GENERATE MILLING STRATEGIES

The most efficient approach for generating a toolpath that defines the precise location of the tool is through Cartesian Coordinate Programming using an offline method (Braumann and Cokcan 2011). Having a model of each scanned fork, with the known location of its geometries to be fabricated, makes this method more suitable than an online programming method. The kukaPRC plugin developed by Robots in Architecture, Vienna offers three command types for Cartesian Coordinate Programming; LIN (Linear Movement), PTP (Point to Point Movement), CIR (Circular Movement). The basic input required for these commands is a plane comprised of XYZABC information where XYZ defines the location and ABC defines the orientation of the end-effector. This information can be easily extracted from planes in Grasshopper where all geometries and data need to be referenced to the robot base. This laid the foundation for the development of in-house toolpath generation for milling strategies: a 3-axis roughing toolpath to remove maximum material at high speed; multi/5-axis finishing toolpath to provide an accurate finish for single or double curvature surface; swarf-milling for fabricating sides of a geometry; and a drilling toolpath for creating holes.

10 Wood Chip Barn's truss.

Basic inputs that include a closed polyhedron—with a minimum of three sides, including its base surface—are required, while parameters like tool length, retraction height, direction of toolpath, tool direction, tool offset, and stepover can be controlled easily. There were three major advantages of this process: 1) The milling toolpath could be quickly modified as the entire algorithm was parametrically defined. 2) Being an in-house developed tool, it gave complete control to the fabricator. Since timber is not a uniform material, quick edits of the toolpath could be performed. For example, milling along the grain direction was found to give a better finish and could by altering the direction of toolpath and stepover. 3) Compatibility issues were prevented as all tasks could be performed in this single interface.

AN ALTERNATIVE APPROACH

Although the process gave rise to a single interface for most tasks, an automated IK solver was still a necessity. With the drawbacks explained previously, Robotmaster still provides a very powerful optimization interface that not only detects the robotic simulation errors, but also provides an intelligent solution to the problem. Hence, we at Hooke Park wanted to harvest this potential by combining the advanced techniques of Robotmaster for optimising robotic simulations and the power of custom-coding in Grasshopper. A process was developed in multiple stages: First, on the Grasshopper platform, the custom toolpaths that also included handling and manipulation of data were executed. Then, a post processor was written on the same platform to generate XYZIJK of the toolpath in Automatically Programmed Tool (APT) code format. The format was represented in XYZIJK, where XYZ defines the Cartesian coordinates of Tool Centre Point (TCP) and IJK defines the vector for tool orientation. Thereafter, the code is imported into the Robotmaster using the Robotmaster Import Utility Tool. Although this provides a two-stage process using two different interfaces, this offers a robust and automated output.

ANALYSIS & CONCLUSION

Robotic fabrication complete, the elements of the truss were pre-assembled in Hooke Park's Big Shed before being erected on site. While a number of small inaccuracies were noted during the assembly process, given the large irregular nature of these components, none were significant enough to have an impact on the global truss geometry. Errors of between 2 mm to 4 mm were primarily attributed to the manual positioning of the trolley along its rail and robotic tool errors. On the later forks to be machined, these errors were significantly reduced and found to be a maximum of 2 mm. With its scaffolding removed, the truss was left self-supporting—its rigid, naturally formed forked

11 Wood Chip Barn Building.

components working together to allow a non-triangulated truss to stand stably. Spanning 25 m from front to back and 10 m side to side, the arching truss rises to 8.5 m at its zenith. The project establishes a workflow for exploiting low-value branched sections of tree into complex and valuable building components without a significant increase in production time when compared to traditional methods. As, we believe, the first full-scale materialization of the concepts described, the Wood Chip Barn project sets out an innovative workflow within which each individual process might be further developed and refined.

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IMAGE CREDITS

Figure 1: Mollica, 2015
Figures 2–6, 8–9: Devadass, 2015
Figure 7: Vegesana, 2015
Figure 10: Bennett, 2015
Figure 11 &12: Bennett, 2016

Pradeep Devadass is an Architect & Robotic Fabrication Specialist, currently working at The Architectural Association's Hooke Park Campus, collaborating with Bristol Robotics Laboratory to develop innovative robotic fabrication methods for manufacturing complex geometries from organic timber elements. He holds a Master of Architecture degree in Emergent Technologies & Design. He is the co-founder of rat[LAB]-Research in Architecture & Technology, an independent research & development organisation based in India. He has worked with various prominent organisations in UK, USA, China, and India. His research work also includes adaptive technologies, advanced fabrication techniques, and algorithmic design methods which have been published and exhibited internationally.

Farid Dailami is Associate Professor for Knowledge Exchange in Manufacturing at Bristol Robotics Laboratory, UWE. Over the past twenty-five years, Dailami has been engaged on a number of projects related to Robotics, Automation, Manufacturing, and Mechatronics. He is also the currently European Co-Ordinator of three Robotics Innovation Facilities (RIFs) located in the UK, France, and Italy, part of the ECHORD++ programme. He has been engaged in developing robotics solutions for automated loading of turbine blades in machining fixtures and a number of other projects concerned with application of automation and robotics in manufacturing.

Zachary Mollica is a Canadian architect and maker whose work explores the integration of innovative digital methods alongside traditional craft knowledge. Zac completed his undergraduate studies at Dalhousie School of Architecture, and has since worked for a number of architecture and design practices in Amsterdam, Lunenburg, Toronto and Vancouver. Completing the Architectural Association's Design + Make programme in Hooke Park over the past two years, Zac led the development of the Tree Fork Truss within the Wood Chip Barn student project.

Martin Self is Director of Hooke Park and Programme Co-Director of the MArch Design + Make programme based at Hooke Park, the Architectural Association's woodland campus. Holding degrees in aerospace engineering and architecture theory, he worked as a consultant engineer at Ove Arup & Partners between 1996 and 2007, where he was a founding member of its Advanced Geometry Group. Projects at AGU included collaborations with architects including Alvaro Siza, OMA, UNStudio, and Shigeru Ban, and artists Anish Kapoor and Chris Ofili. He has taught students in realising design-build projects at the Architectural Association since 2005.

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