FAB RICA TE

INFINITE VARIATIONS, RADICAL STRATEGIES

MARTIN SELF / EMMANUEL VERCRUYSSE
Architectural Association, London

The AA's satellite campus out in Hooke Park, Dorset, is the headquarters of its Design+Make programme and operates as a laboratory for architectural research through 1:1 fabrication. In an environment that combines forest, studio, workshop and building site, the large-scale fabrication facilities act as a testing ground where students devote time to advanced speculative research through a hands-on approach.

Designing and building architecture in the woods: within an idyllic forest ecosystem that is both material library and site, the programme explores how natural materials, craft knowledge and new technologies elicit exciting and unpredictable architectures while implying a deep connection between site, construction and tree species. It provokes a critical approach to designing and manufacturing – one which encourages a symbiotic relationship with the variability found in nature.

Design+Make's position, embedded within the forest, nurtures the students' attitude towards design, imbuing it with an expanded sense of material implications. They are exposed to the long-term investment of time and energy required for timber growth and the forestry processes required to manage it. This living material is formed by its spatial and environmental conditions, and the management of a forest is in many ways an act of design where it is possible to guide the structure of the trees it contains. In this way, design thinking begins under the canopy of the forest itself. The forest's delicate experiential qualities are due in no small part to its infinite variability and, rather than merely being a context for the work, the forest itself, with its material and structural diversity, becomes the inspiration for a way of working.

Digital design and fabrication tools are often used to develop non-standard series of components from standardised materials. Timber is usually considered as a rectilinear material, often reduced to sheets, planks or beams before having a complexity returned to it by milling procedures. And yet trees already present a naturally formed non-standard series – each is wholly unique. The Design+Make programme provokes an alternative conception of material form in which inherent irregular geometries are actively exploited by non-standard technologies.

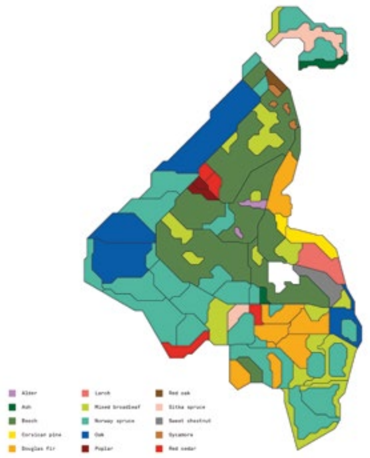
1

Woodchip Barn

In a standing tree, the naturally occurring branching forks exhibit remarkable strength and material efficiency, being able to carry significant cantilevers with minimal material. Deriving non-standard timber components from wood's inherent forms, the truss of the Woodchip Barn is presented as a unique timber structure that makes full use of the capabilities of new technologies such as 3D scanning and evolutionary optimisation of the placement of each discrete component within a structurally determined arch, along with customised robotic fabrication. The rationale for this approach is that the diverse characteristics of onsite material can be exploited directly without wasteful industrial processing, while simultaneously providing fertile territory for an unconventional design attitude. The Woodchip Barn employs twenty beech forks within an arching Vierendeel-style truss. The building provides $400m^3$ of storage for biofuels and will enable the Hooke Park estate to use its own timber for renewable heat production.

While timber has seen a resurgence as an advanced architectural material, the complex and organic forms pursued are generally not attributable to the geometric and anisotropic structural properties of wood. Instead, fabrication processes generate complex components from standardised wood products to ensure consistency. An ambition for the project was to exploit the moment-resisting capacity of tree forks. In a standing tree, the naturally occurring forks exhibit remarkable strength and material efficiency[1], and before processing already present what digital tools are commonly employed in pursuit of: a non-standard series.

The Hooke Park woodland was first surveyed for trees with appropriately forked trunks, resurrecting the historic strategy of shipbuilders travelling into the woods equipped with a set of templates that described the specific forms they required to construct various components[2]. An initial photographic survey of 204 standing beech trees provided approximate two-dimensional fork representations with enough detail to make informed decisions about which trees to cut down. From an analysis of this database, a shortlist of 40 forks were selected for felling, from which 25 were successfully harvested. A detailed photogrammetric 3D scan was made of each of these in order to capture their complex forms. From the resulting surface mesh geometry, medial curves were extracted for each fork using a polygon-based method in which transverse sections were cut through each one at regular intervals to obtain



2

the outer profile of their geometry. Following this, local best-fit diameters and centroids were calculated for each profile's section.

The structural form of the arching truss was determined, in discussion with the Arup team, to have the appropriate inverted-catenary form for a compression structure and a cross-sectional geometry which could accommodate the dimensions and angles of the sourced tree forks. The choice of an equilateral triangular section of typically 90cm side dimensions was found to work well by both providing stability to the arch and being a size on which the forks could be fitted. The structure is composed of two planar inclined arches in a distorted Vierendeel configuration that exploits the moment capacity of the forked junction. The structure lands at four points, the front slightly wider than the rear, with four inverted tripod legs supporting the robotically fabricated mid-section.

The positioning of each forked component within the truss was determined iteratively using an organisation script that sought an optimal arrangement of the components to best satisfy structural and fabrication criteria. This was achieved through evolutionary and simulated-annealing procedures carried out in the Galapagos solver within the Rhino-Grasshopper environment. Within the optimisation, there were two levels of position adjustment: the global swapping of components between possible locations in the structure, and the local shuffling of components in which each element was slid along the target arch curves to best find its location. The key criterion was to minimise deviation of the forks' medial curves from the target curves of the idealised arch centrelines. Further criteria were applied to place the larger diameter trees where axial forces were greatest and to deal with specific geometric constraints (for example, at the points where the truss bifurcated to form its legs). The optimisation was improved by indexing the component set according to the geometric strategy and by sequencing the placement so that the most critical positions were populated first[3].

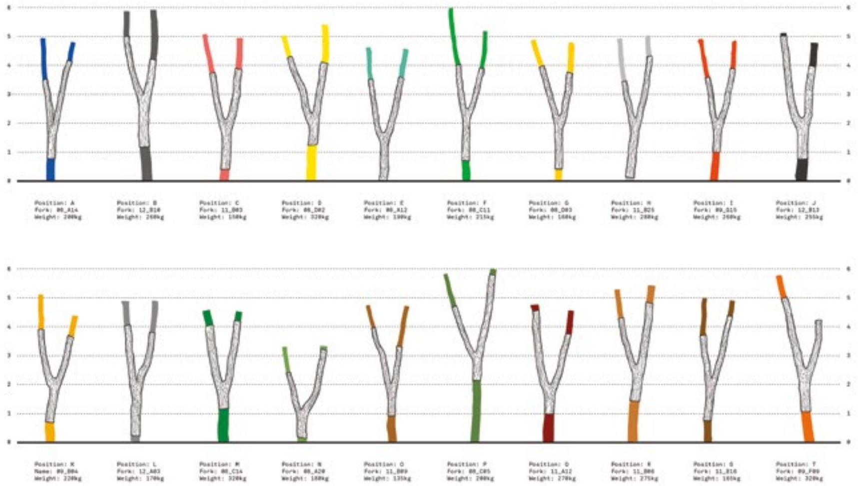
The outcome of the optimisation process was a three-dimensional arrangement of the tree fork geometries in which the key setting-out nodes were coincident with the underlying target tree curves. The combination of this nodal data with the element medial curves and diameter data was used to derive the digital fabrication information for the machining of connecting features into the raw tree forks using a router spindle on Hooke Park's Kuka KR-150 6-axis robot arm. The connections were configured to achieve transfer for compression forces through timber-to-timber bearing and to reinforce these with steel bolts when additional tension or shear strength was required. The connection surface geometries varied in different parts of the structure and consisted of either planar face-to-face surfaces between elements along the chords or mortice-and-tenon joints in which a distorted elliptical cone geometry was found to best satisfy the structural and assembly constraints.

The robotic milling procedure consisted of first defining 3D volumes for router subtraction of connection shapes from the wood, then determining an appropriate robot toolpath to achieve that geometry. The key requirement was to produce precise relative positions of the machined surfaces such that dimensional accuracy during assembly could be achieved. Two strategies were developed to enable this. Firstly, a consistent referencing system was established which ensured that a tree fork component could always be correctly located in space in the virtual modelling environment, the machining cell and the

1. Timber is usually considered as a rectilinear material – its irregular forms reduced to standard sections. The work undertaken proposes an alternative concept of material form in which inherently irregular geometries are directly exploited by non-standard technologies.
Image: Valerie Bennett.

2. Design+Make projects attempt to exploit the inherent characteristics of the approximately 16 tree species found within Hooke Park. The Tree Fork Truss project was developed from the naturally occurring form of 25 distinct beech trees.
Image: Zachary Mollica.

3



4

5

3. The planar geometry of a Japanese joint lends itself perfectly to the specific machining operations of robot and chainsaw.
Image: Valerie Bennett.

4. An idealised structural volume was established. A Grasshopper script was developed to allow it to be dynamically populated with real fork geometries. This image shows the 'trimmed' form of each fork contained within the final built structure.
Image: Zachary Mollica.

5. The robot arm machining one of each fork's two bearing surfaces. The digital model was translated into fabrication information with which a 6-axis robotic arm transformed each fork into a finished component.
Image: Pradeep Devadass.

ultimate assembly of the structure. This was achieved by physically drilling three reference holes on the truss that were tracked in the 3D models and subsequently used to support the fork during fabrication and assembly. The second strategy was to accept that it was difficult in practice to be sufficiently precise in modelling the exact surface geometry of the natural tree (an accuracy of +/-10mm was typical, rather than the +/-2mm required) and so to make the locating of the milled face independent of the outer tree surfaces. This was achieved by defining subtracting volumes larger than the tree as scanned and accepting some redundant milling of air rather than wood.

6

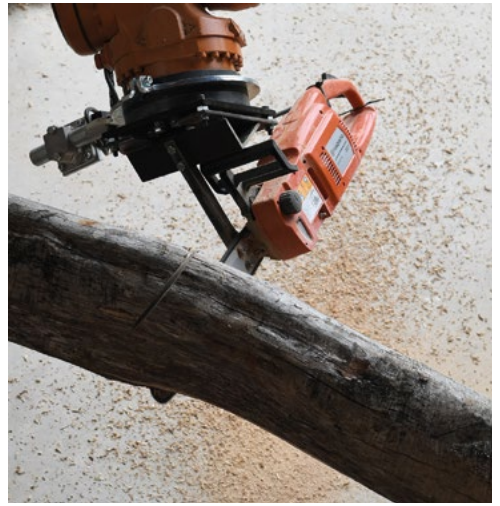
Following the fabrication of the fork components, the truss was pre-assembled in two halves in Hooke Park's assembly workshop. Again, drilled reference points were used to correctly locate the fork components within an erection jig whose support geometry had been extracted from the digital model. The precision of the robotic fabrication proved successful and only occasional manual woodworking was needed to achieve a well-fitting fully bolted assembly. This was further demonstrated when the two truss halves were crane-erected onsite and the full 25m arch was successfully de-propped. The building was completed with the addition of push-walls to contain the woodchip and a conventional timber-framed roof supported by the arching truss.

The building is presented as a demonstrator and validation of an approach proposed in various forms over recent years[4,5] in which new computation tools are applied to the configuration of material elements so that the inherent geometry of those elements is exploited. In this case, the underlying arch geometry was largely predetermined (i.e. anticipating typical geometries of the forks but not directly determined by them) and the optimisation was limited to locating components within that geometry. Thus a development of the method will be to enable the underlying structural form itself to self-organise through the varied components acting as agents towards a set of spatial and structural goals.

Advanced and bespoke system operations

Other strategies are now in place to enhance this approach, enabling more complex structural experiments. For instance, establishing the horizontal rotational seventh axis to operate in synchronisation with the 6-axis robot arm has been instrumental to advancing the manipulation of non-standardised timber. This configuration, capable of carrying large tree segments between two modified lathe end-stocks, means that the robot's end effector can access any point along the length of the tree log. The ability to carve a tree much more freely opens up new formal, structural and aesthetic potentials. The machining operations can be applied locally and the sculpted profile could be structurally optimised – analogous to the geometry of bone or open-grown trees – and gives timber as a material a new 'plasticity' (in the art history sense of the word) of form that is difficult to achieve with other materials.

The application of a variety of end effectors provides yet more possibilities for the manipulation of the material. The chainsaw – a tool not known for its exactitude – gains an augmented level of precision and control when wielded



7

8

by the large Kuka KR150 robot. LiDAR scanning technologies form an essential component within these advanced system operations, not only providing a fully calibrated workspace but also crucially allowing operations on naturally formed geometries with surgical precision.

3D scanning allows us to treat something incredibly unique and complex in form in the same way that we might treat a standard plank of timber. The ability to scan the space of machining to align the worldview of the robot with the actual position of a non-linear object like a tree trunk allows for more flexible machining strategies, as the calibration becomes more organic. The digital model and the physicality of machining on this scale can converge with previously unimagined precision.

The innovative and radical nature of the approach employed at Hooke Park lies in the strategic precision with which Design+Make teams can augment the natural geometry grown there. The variability and complexity is natural – our machine strategies play to the beauty and strength of this complexity and follow its lead[6]. In this way, we are employing the tacit knowledge of a material on which craft relies, while exploring the possibilities afforded by the pinpoint precision of the technological eye and hand of scanner and robot.

The aim is to use robotic technology not forcefully, for power, repeatability or wilful formalism, but delicately, for the strategic augmentation of a natural and complex logic. It is with this attitude that we have established the campus as a 'continuous laboratory', where Design+Make operates as an agency of architectural innovation and presents a unique and alternative vision for architectural education.

6. The front half of the truss being assembled within the Big Shed. The finished elements of the truss were pre-assembled in two halves, each approximately 9 x 6m. A large jig allowed their accurate arrangement. Image: Zachary Mollica.

7. Precision augmentation of naturally formed geometries utilising robotically controlled chainsaw. Image: Zachary Mollica.

8. The natural forked geometry undergoes localised modification to facilitate a structural connection. Image: Valerie Bennett.

Acknowledgements

The Woodchip Barn was designed and built by Design+Make students (Mohaimeen Islam, Zachary Mollica, Sahil Shah, Swetha Vegesana and Yung-Chen Yang) under the tutelage of the authors, with Charley Brentnall and Toby Burgess. It was fabricated and constructed with the support of SummerBuild volunteers, site project manager Jack Draper and the Hooke Park forestry and workshop team (Christopher Sadd, Charlie Corry Wright and Edward Coe). Pradeep Devadass oversaw the robotics development, and engineering support was provided by Arup (Francis Archer, Naotaka Minami and Coco van Egeraat).

Notes

1. Slater, D. and Ennos, R., 2014, 'Interlocking Wood Grain Patterns Provide Improved Wood Strength Properties in Forks of Hazel (Corylus avellana L.)' in *Arboricultural Journal, January 2015*, Berlin, Springer-Verlag.

2. Matthew, P., 1831, *On Naval Timber and Arboriculture*, Cambridge, Harvard University.

3. Mollica, Z. and Self, M., 2016, 'Tree Fork Truss: Geometric Strategies for Exploiting Inherent Material Form' in Adriaenssens, S., Gramazio, F., Kohler, M., Menges, A. and Pauly, M. (eds.), *Advances in Architectural Geometry 2016*, Zurich, p.138-153.

4. Jannasch, E., 2013, 'Embodied Information in Structural Timber' in Cruz, P. (ed.), *Structures and Architecture: New Concepts, Applications, and Challenges*, London, CRC Press, p.2176-83.

5. Schindler, C., Tamke, M., Tabatabai, A., Bereuter, M. and Yoshida, H., 2014, 'Processing Branches: Reactivating the Performativity of Natural Wooden Form with Contemporary Information Technology' in *International Journal of Architectural Computing*, Vol. 12, No. 2, p.101-116.

6. "I don't want to change the material, I want to follow its lead," Giuseppe Penone quoted in interview with Robert Enright, 'The Perfection of the Tree and Other Material Concerns' in *Border Crossings*, December 2013, available at http://bordercrossingsmag.com/article/the-perfection-of-the-tree-and-other-material-concerns (accessed 29 December 2015).