Autonomous Architectural Operations

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ABSTRACT
The research set out in this paper investigates the conception, testing, and implementation of an advanced and bespoke workflow. By hybridizing a diverse set of technologies and processes, an innovative fabrication strategy was developed that combines large scale glue-laminated timber frames with a robotic band-saw application.

The design strategy was influenced by a number of key preoccupations: exploring the relationship between drawing and making, evenly distributing analogue and digital technologies, and advancing alternatives modes of architectural practice. The project regards intuitive design processes as an important driver and looked to apply digital tools lightly, aiming to precisely embed them within established timber fabrication processes.

This workflow was tested through the design and fabrication of a timber skeleton that provides the structural system for a library building at Hooke Park and acts as an articulated armature supporting the library’s envelope and accommodates its internal workings. Through the production of the sculptural skeleton, the project challenges conventions of existing methodologies and ultimately brings about a morphologic innovation in timber construction through the closed geometry glulam component.
INTRODUCTION

The Skeleton: A Design Test-Bed
The aim of the research—which runs in parallel to teaching within the Design + Make course at the Architectural Association—is to generate new protocols within the realm of experimental architectural fabrication, and to foster an attitude towards making architecture that allows tacit knowledge and intuitive acts of design to work hand-in-hand with technological innovation, such as precision 3D scanning and the coded protocols of robotics. By doing so, we aimed to develop an alternative practice that reconnects architects with the physical production of architecture.

The design and fabrication of a structural timber skeleton with the Design + Make students provided an opportunity to conceive, test, and implement an advanced and bespoke set of system operations. The skeleton itself provides the structural system for a library building, which also contains an archive, study and work space, and acts as an articulated armature supporting the library’s envelope and accommodates its internal workings. By hybridizing a diverse set of technologies and processes, an innovative fabrication strategy was developed that combines large scale glue-laminated timber frames with a robotic band-saw application.

The timber fabrication processes merged aspects of conventional glue-lamination with the technique of cross-laminated timber (CLT) allowing for the production of large-scale volumetric frames. These rough frames were then positioned and calibrated in the robot cell as ‘bespoke stock material’ and operated upon by the robotically controlled band-saw to produce delicately sculpted components, carved precisely by the robot arm to form a cohesive structural system. This explicitly sculptural structure was successfully assembled on site through a set of highly choreographed manoeuvres.

Through exploring and developing this design-to-production workflow, we sought to embed digital tools within established timber fabrication processes, to challenge the conventions of existing methodologies, and ultimately to bring about a morphologic innovation in new timber construction through the closed geometry glulam component.

Within conventional glulam strategies, fabricated components can be divided into three categories; straight elements, single-curved elements, and double-curved elements. These types inherently present an increasing complexity in production and consequently cost. The
production process of straight components is uncomplicated, as straight machined planks are laminated in a simple linear press. Curved geometries, however, require complicated and often compound or modular forming processes. Once formed, these laminated components are operated upon to achieve connections and a surface finish. With the production of the closed geometry glulam component, this research explores new territory into non-standard glulam geometry.

Many of the most advanced glulam projects are fabricated in the extensive production facilities of Blumer-Lehmann. Particularly the fabrication of the structure for the Cambridge Mosque, designed by Marks Barfield Architects, has an important relevance to the skeleton project. Infinitely more complex, the project consists of 2746 beam segments and more than 6,000 joints reduced to just 145 different types of components and 23 different types of glulam timber blanks (Bau.Werk 2019). The rationalization of the structure into different types and components had a large significance, as it assisted in composing the structural logic of the skeleton.

Within the fast evolving world of glulam technology, current research is focusing on the optimization of grain direction within constituted components. The advanced research by Tom Svilans—an Innochain PhD fellow also affiliated with Blumer-Lehmann—explores two strategies within this field: a discretization of components into triangular of tetrahedral elements, and a multi-scalar approach that links together the digital model of the architectural element with the digital model of the timber assembly from which it is machined (Svilans et al. 2018).

The research reinforces the logic behind the closed geometry glulam component where the planks are cross laminated using a very specific geometry. This geometry is informed by the performance requirement within the larger structural system and attempts to keep the grain orientation as consistent as possible

BACKGROUND

As a global positioning of the work, the research aims to unapologetically side-step the mundane world of architectural practices, and to explore design at the point of physical production. Recognizing the value of the direct engagement with material and positioning the act of making at the centre of the design process are the guiding principles within the Design + Make course for the active development of alternative practices of architecture.

This prerequisite principles fundamentally direct the development of fabrication operations as it pilots them towards a replicable model. All tools and processes are designed to be replicable outside of the comfort zone of an educational structure. This model is met in the skeleton library project through: applying our second hand robotic arm, the reappropriation of the second hand band saw into a robotic end effector as the main fabrication tools, and the use of photogrammetry for calibration and alignment. This strategy endeavors to demonstrate an alternative vision for architectural education and, expectantly, for the longer term influence on the world of architectural practice.

The location of the research—Hooke Park—plays a central role within this ambition as it offers an extraordinary opportunity for experimental fabrication with timber through the provision of a closed-loop system. This qualitative condition—of combining the working woodland with the design studio, workshop, and building site—grants an extensive level of autonomy.

The on-site large scale fabrication facilities further advance opportunities to foster innovative approaches to the production of architectural constructs, as it provides the laboratory conditions to autonomously devote time to speculative research. This allows for the invention of advanced and bespoke workflows that explore new territo-
ries between the natural and the artificial. The merging of the site of material production [the woodland] with the site of fabrication leads to the formation of a new materiality.

DESIGN AS A TACIT PROCESS
Methods
Timber is experiencing a resurgence as a building material, largely due to its aspect of sustainability. As previously stated, for experimental fabrication with timber, we are taking full advantage of the fabrication facilities and our embedded position within the forest at Hooke Park to nurture our attitude towards fabrication, as it provides a living material to work with. Previous research focused on largely under-explored capacities of wood; in the WoodChipBarn project, the inherent form of natural forked trunks was employed to configure the structural Vierendeel truss (Vercruysse/Self 2017). In the Sawmill Shelter, we exploited the exceptional integral strength of timber in tension as the main principle in the roof’s construction.

With timber a given as the material agent of the project, the design strategy was loosely informed by the elegance of Carlo Mollino’s furniture. A language for timber construction was explored that was able to take on the agility and playfulness that timber furniture allows—a scale which is much more easily able to embody the lively character of a sketch.

Oscillating between intuitive acts and precise operations, the initial sketches provided the underlying structure for CAD data and, subsequently, g-code for the flat bed router. The process was an iterative one as constructed scale models were analyzed, annotated, re-assessed and redrawn, to begin the process of translation from sketch to code once more.

The particular interrelationships between the made and the drawn allow for the design to incrementally advance towards larger scale constructs and eventually a final translation towards 1:1 robotic fabrication.

Structural Logic
The skeleton has exceptional structural requirements; in addition to accommodating the program of the library, it also needs to carry and form the anchor point for the large lateral loads imposed by the tensile roof of the adjacent [yet to be build] lecture hall. These lateral forces played a key role in influencing and fine tuning the global geometry of the structure. Several key principles were identified to define a clear structural strategy, many of them extracted from Mollino’s table. The structure consists of a set of interlocking closed planar frames to be assembled into the three-dimensional skeleton. The design was...
Inclining the central frames supports the parallel frames at mid-span and reduces any horizontal bending. This allowed keeping a relative homogeneous size of all the structural members throughout the structure. The structural tactics of the skeleton attempt to largely compensate for the forces generated by the tension roof; however, additional components, such as stiffness throughout roof and wall planes, are required to achieve completely stability.

Elegant through their simple logic, the connection methods for the frames were also derived from Mollino’s table: the different frame typologies join face to face where the connections are planar and perpendicular in the occurrences where face and edge meet, and all connection aim to reduce complexity. The strategy permits not only for a quick assembly but also allows for the largest amount of tolerance for the connections.

These complex structural principles were developed by the generous support provided by the structural engineering team at ARUP. This input steered the geometric configuration of the frames and largely supported the technical feasibility whilst allowing space to explore the sculptural possibilities of a robotically controlled band saw.

Current advancements in timber construction focus mainly on the development of highly engineered products. The process of glue lamination—particularly when combined with cross lamination—offered up a rich set of opportunities to break down the various sub-processes and tailor them towards the specific needs of the skeleton structure.

Glu-lamination allows for larger and longer components than would be possible with traditional solid sawn timber, as it sidesteps the constraints inherent in the size of trees. The product ends up being stronger and stiffer than machined solid timber and has the potential to facilitate a higher material efficiency. Through this process of reconfiguring, the size and shape of glu-lam components is largely defined by manufacturing, transport, and handling capabilities. Further advancements in structural adhesives support the ability to produce prefabricated components to precise specifications. The curing time of the glue determines the time frames of the different operations used to produce the components. High bond strength can be achieved through foaming penetration filling the bond cavities, and this allowed us to use timber with a moisture content of up to 16%.

The procedures that precede the gluing process were instrumental in gaining a tacit understanding of the characteristics and properties of the timber. For instance, the
planing of the wood opens up the fibers that optimize gluing, and a process that simultaneously allows for the scrutiny of the quality of timber board by board. As we sought to maximize the continuity of the grain direction of the wood, it was necessary to eliminate any strength-reducing characteristics, such as excessive knots or warped pieces.

As described, conventional glulam typologies are divided into three categories. Exploring the potential of the closed geometry aims to add an additional type. Within the closed-frame geometry, a change of direction is required, and the grain orientation plays a fundamental role in achieving the structural requirements that the frame needs to fulfill. The structural quality was further enhanced by applying a cross lamination, and combining this with the advantages of a closed geometry, the components were made stiffer through their composition.

Once glued and clamped to a uniform pressure for up to 12 hours, the cross laminated glu-lam frame is seen as a new type of blank—the raw stock material upon which a number of operations are performed and which lead to a final timber component. The blank is no longer neutral or uniform object; it is bespoke, its geometry prescribed by specific design information.

**ANTICIPATING THE ROBOTIC OPERATIONS**

To facilitate the forming processes, an assembly bed of 6m x 2m was produced to accommodate all the component sizes. This jig performed a strategic role within the prescribed workflow, acting as the confluence of the analogue phases and the digital data that would guide the robotic processes. CNC templates, which marked out the required geometry, formed the first digital control mechanism.

A dry fit strategy served as a rehearsal to move through the processes and eliminate any potential discrepancies that could hinder the fabrication process. This led to resolving issues with positioning through the use of reference dowels to precisely lock individual planks in the correct location.

Due to the large size of the components, the CNC template helped to further transcribe the positional information of the reference system we formulated in order to calibrate the components’ location within the robot cell.

This process also provided a deeper analysis of the clamping tools. To achieve a constant pressure cover across the varying widths that occur within the global structure over a hundred bespoke clamps were made each with varying length.
Reconfigured Tools

This bespoke fabrication workflow required the fabrication of a new end-effector; a tailor made band-saw mounted on the 6-axis robot arm. The reappropriation of the band-saw plays an important role within the research, as it allows the exploration of robotic processes alongside firmly rooted traditional fabrication methodologies.

A band-saw as end-effector has been applied to timber fabrication within a number of recent projects. The project Bandsawn Bands, by Ryan Luke Johns and Nicholas Foley, looks to advance the material efficiency offered by the tool set up and investigates the possibility to derive forms from a nonstandard grain configuration (Johns, R.L. and Foley N. 2014).

In Philip Yuan and Hua Chai’s Robotic Wood Tectonics, the team explores potentials of robotic band saw cutting technology in the construction of complex wood structures and argues that the technique provides a feasible solution for producing curved wood beams without the immense time consumption of CNC milling method (Yuan 2017).

Our main ambition for this tool set up was to achieve the detailed component shape; it needed to be capable of making the accurate cuts necessary for the elements to meet precisely and produce the sculptural curving fillet at the edges and corners of each frame. Gaining an understanding of this new tool was vitally important.

After the disassembly of a second hand saw, a bespoke band-saw was developed, disregarding all non-essential components and widening its cutting gate to maximize cutting access. Converting this traditional tool into a robotic end-effector fundamentally altered its performance. The band-saw gains an augmented level of precision and control when wielded by the Kuka KR150 (Vercruysse 2018).

New rules emerge governing the forms to be produced by the newly configured tool. The behavior of the tool has changed and the ways in which the tool can be used...
fundamentally altered. The traditional relationship between band-saw and material is reversed as the saw, animated by the robotic arm, travels towards the stock rather than the other way around.

It allows for the removal of large quantities of stock material in a single cut but it also offers the opportunity for more sculptural applications through delicate cutting procedures with the minimal cut of a band-saw blade.

Different versions of the band-saw were conceived to facilitate specific applications within the design. The geometry of Band-saw V1, particularly the connection back to the robot, proved problematic in accessing tight internal corners. The optimization process led to Band-saw V3, where its geometry largely eliminated collisions between tool stock, material, and desired geometry.

The fundamental operational principle of the bandsaw is that the blade behaves as ruled surface, a surface that can be swept out by moving a line in space (Weisstein 2019). As the bandsaw has a depth, its behaviour deviates from this idealised mathematical definition. The toolpath generation takes into account this depth and develops isoparametric curves, allowing cutting surfaces to be created based on the dimension and behaviours of the bandsaw blade. Within the production of the skeleton components cycloid and conoid cuts were deployed almost exclusively to avoid the necessity for the blade to make severe changes in orientation. This minimised excessive degrees of torsion, maintained the vector alignment, and evaded any wandering of the blade.

It was not our intention to strive towards a fully automated process; we allowed for significant space for analogue and more intuitive interventions. Occasionally the tooling set up was unable to finish a component due to reach or depth issues. In those instances the tool was used to provide indicating markings to guide manual finishing.

Alignments and Calibrations
Unlike traditional craftsmen, the robotic arm has no need to set out its cuts as it enacts the invisible instructions which have been endlessly rehearsed through digital simulations. This reference system cannot disappear completely, especially with the immediate need to machine from multiple positions, as we were operating upon large scale closed frames. Therefore, there was a need to devise a logic that carefully considered the physical orientation of both tool and glue-lam blank. This required a method of stock-holding that allowed for the relocation of the frames within the robot cell whilst maintaining positional accuracy and addressing the need for both work-piece stability and maximum access.

This layer of information for the calibration and referencing process was inscribed through the CNC template first used at the assembly stage. These markers clearly defined points which the robot could re-reference in order to construct the plane rotation of the frame within the cell. This also allowed for further verification, linking the analogue assembly process with the robotic machining, and creating an adaptable machining environment where the stock material could quickly be moved to new positions to machine additional faces which were originally out of reach.

Physically this meant that the holding method for frames needed careful consideration, as the robotic arm needed to machine large scale pieces varying from 2.5m x 2.5m to a maximum of 3.0m x 7.0m. A set of bespoke skates were fabricated, adjustable in height to facilitate this complex handling and to allow the large glu-lam blanks to move freely in the cell, overcoming the limited machining area of the robot. The hardware components, the skates and the band-saw reconfigurations, were made possible by the ingenious fabrications of Charlie Corry-Wright.

**Precision Feedback**

At a first glance, our digital workspace appears to contain an absolute precision. The process of physical production operates within a different dimension as material behaviors, and aspects such as gravity distort this precise world. Next to the CNC templates, scanning technologies form the connective tissue between the digital space of simulation and the physical realities of material production. They provide not only a highly calibrated work space, but also crucially allow for precise interrogations of the freshly machined components.

Photogrammetry minimizes the divergence between the digital and the material as it creates a direct feedback loop between the digital (design and operation) models on one hand, and the material behavior inherent to timber and the physicality of machining on this scale on the other. This allowed for a continuous assessment of components and an ongoing revision of the digital model space.
It generated the opportunity for intervention between the strictly sequenced and automated processes. The appearance of this temporal window—a space to capitalise on unexpected opportunities and discoveries—generated a true delight within the work because it guaranteed the involvement of the human hand within the construction and fabrication processes.

The different scanning strategies continued beyond the production phase and featured heavily in the assembly process, as the prefabricated timber frames were assembled into two super structures on site. After the skeleton was fully assembled, a final Lidar scan allowed further scrutiny in search of deviations and discrepancies generated by the accumulation and the self load of the large frames in relation to the digital model.

CONCLUSION
CRAFTING THE CODE
The project was driven by a desire to explore the production of architecture intuitively through iterations of drawing, craft and code, and employs tacit knowledge of a material whilst exploring the possibilities afforded by the pinpoint precision of the technological eye and hand of scanner and robot. These scanning technologies further reinforced a fundamental attitude towards the digital—to be understood very much as augmentation of the analogue, rather than a substitute.

Through the development of this design to production workflow, we sought to embed digital tools within established timber fabrication processes. The bespoke workflow and tooling tested the technical feasibility and aesthetics of sculpted glu-lam and was successfully applied in the production of the skeleton structure. Digital tools were applied, not to negotiate the formal language but to take up a strategic position to facilitate the materialization of the components.

The final form of the frames responds to an evolution of the language that started off with a highly intuitive sketch which got enriched along the trajectory by architectural, structural, and technical input. The closed geometry glu-lam component looked to add a typology within existing and conventional glu-lam strategies. Its structural and fabrication logic utilizes the uncomplicated production process.
of standard straight components and combines it with optimized grain direction, an aspect borrowed from CLT components. This combination offers exciting opportunities within timber construction as straightforward forming processes are deployed to easily achieve geometric complexity.

This bespoke oriented glue lamination combined with the sculptural possibilities of a robotically controlled band saw provokes a new language of fabrication. The reappropriation of the band-saw in conjunction with robotic processes, allowed for the precise embedding of digital tools. The strategy also permitted us to challenge the conventions of existing methodologies while safeguarding techniques firmly rooted within traditional fabrication methodologies.

All these aspects collectively allowed the research to function at an exceptional level of autonomy within the field of architecture. It approximates a state of autarky as it furthers the vast potential of timber applications.

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REFERENCES


Emmanuel Vercruysse holds a set of leading roles at the Architectural Association. He is Co-Director of the Postgraduate Design + Make course based at the AA’s satellite campus in Hooke Park, positioning the campus at the forefront of architectural research through prototyping and large scale fabrication. In his roles as Curator of Robotic Development and Director of the Robotic Fabrication Visiting School, he has developed research in experimental Robotic Fabrication both in Bedford Square and at Hooke Park. He also teaches at the Bartlett School of Architecture, University College London, and is involved in numerous collaborative practices and research groups, including the art and architecture practice LiquidFactory; the Field Robotics group RAVEN; robotic fabrication lab ProtoArchitecture; and the RIBA award winning experimental architectural practice Sixteen*(makers). He has taught at the Bartlett School of Architecture, UCL since 2007.