



# Robotic processing of crooked sawlogs for use in architectural construction

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## Abstract

In this paper, ideas and methods for utilising crooked sawlogs in construction are presented. The paper discusses a current problematic reality and, through a selected scenario, proposes a workflow that handles a series of challenges that arises when working with irregular wood. Through an investigative working method and by utilising computation and digital manufacturing technologies, the workflow integrates material properties with architectural design tools. The research focusses on oak logs which have been discarded by the timber industry due to their irregular shapes. Oak is a hardwood with structural properties, but often grows into crooked geometries. Through procedures for 3D-scanning, data handling, analysis, and evaluation methods, informed machining and utilisation of the logs are made possible. Numerous crooked sawlogs are handled in parallel physical and digital stockpiles. The digital stockpile holds layers of information generated from the sawlogs. When given an input geometry, the workflow matches the geometry with sawlogs found in the digital stockpile, and using procedures for developing and detailing, a realised version of the geometry can be machined and constructed using digital fabrication methods. The workflow includes multiple custom-made methods and algorithms for handling the complex and different shapes and data of crooked sawlogs in a highly digitised machining and fabrication environment. A constant link and the dialogue between digital data and physical reality are maintained and used actively in both design and fabrication strategy. The suggested up-cycling of irregular sawlogs using non-standard methods is a critical articulation of today's linear material economy as the research illustrates how the natural forms and properties of materials can be used to rethink existing design and material practise. This paper is an expansion and further development of work presented at ACADIA 2019 (Larsen et al. in Ubiquity and autonomy, The University of Texas at Austin School of Architecture, Austin, 2019).

**Keywords** Natural wood · Robotic fabrication · Computation · Material analysis · Research by design

## 1 The natural properties of wood

Wood is an anisotropic material, and the length, directionality, strength, and elasticity of the grains are particular to each species (Hoadley 2000). The research project is investigating the properties and capacities (Delanda 2007) of wood through digital machining methods, metrology, scanning techniques, and hands-on experience. By cutting, splitting, bending, sawing, milling, scanning, X-ray, tomography, and printing, a series of experiments illuminate the properties of

wood by paying attention to the unique material and processing methods in different ways (see Figs. 1, 2, 3).

The experimentation seeks to let the small-scale behaviours and particularities of wood inform and inspire design potentials, similar to research projects carried out by ICD/ITKE research (Menges et al. 2016), e.g., through their HygroScope (Menges 2012) and HygroSkin (Krieg et al. 2014) projects. Simultaneously, this research project embraces, investigates, and processes the outer geometry of natural wood. This has also previously been explored in the Ratatosk Pavilion by Helen Hard (Stangeland et al. 2012), recently at University of Michigan (Buelow et al. 2018) and through the immense work produced at Architectural Association Hooke Park (Mollica and Self 2016). Hooke Park was visited during the early stages of this project because of their enormous experience with both physical and digital

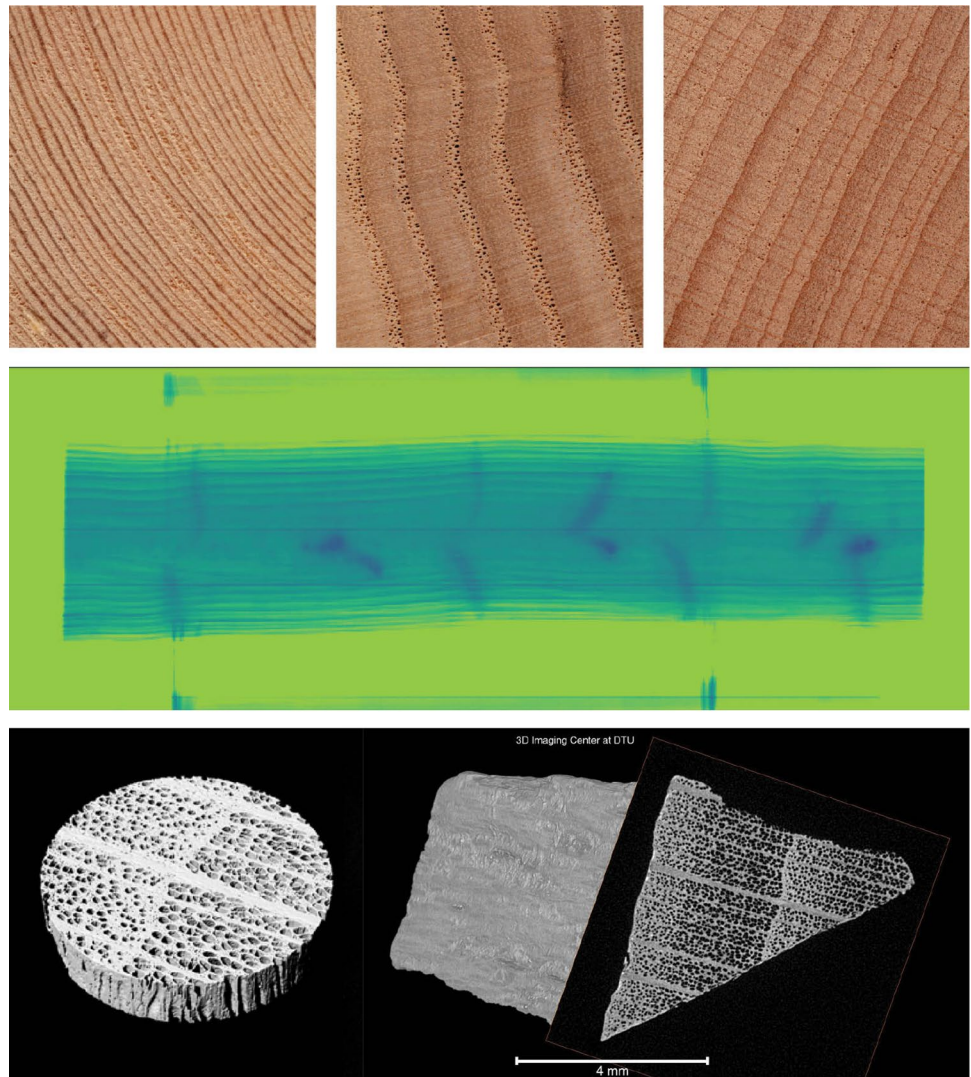
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**Fig. 1** Top: Macro photos showing internal patterns of pine, beech, and ash. Mid: X-ray scanning of spruce clearly shows the orientation of grain structure and the location of internal knots (done in collaboration with Niels Bohr Institute). Bottom: CT scans are used to construct voxel and mesh representations of the internal wood structure (scanning is done in collaboration with by DTU Imaging)



**Fig. 2** Logs processed with a milling tool mounted on a six-axis robot, demonstrating the exact coherence between the geometry of the scanned logs and the milling tool paths. Left: A 3D model with isocurves. Right: Real log with milled isocurves



handling of natural wood, and their achievements are both a huge inspiration and a direct source of knowledge.

Another important source of knowledge for this project comes directly from visiting and understanding the current wood industry. A research trip through Finland mapped out the industry and workflow from harvest to products and,

especially, the heavy use of highly advanced technology made an imprint on the research agenda.

Different types of scanning and various robotic machining processes using a chainsaw, band saw, and spindle have been build and developed for this project to test and understand actual the properties of wood. The aim is, however, to



**Fig. 3** Crooked oak log cut into curved boards

expand on the existing research context outlined above, and bring forward findings that suggest more holistic approaches to using natural wood in construction. This means that the actions taking in this project can be seen as testing scenarios trying to suggest approaches not far away from the workflows of the high-tech wood industry. It also means that this research seeks to not only develop strategies for one-off pavilions. Instead, the ambition is to produce whole and agile workflows that enable the generation of multiple solutions and provides comprehensive information for handling and machining the natural wood into building systems.

## 2 Utilising crooked sawlogs

Using wood in construction has a positive impact on the carbon dioxide emission level. By enabling carbon sequestration and replacing building materials with higher levels of carbon dioxide emission (Laturi et al. 2008; Gustavsson et al. 2006) with wooden building elements, the relevance of using non-uniform wood in architectural construction is not limited to the geometrical and tactile potentials. Limiting waste of harvested timber and utilisation as much

of the cut-down wood in lasting applications benefit the environment directly. Therefore, this research includes an important sustainable discourse where material particularities are applied to specialised uses instead of wasted or down-cycled.

The forestry and sawmill industry take several actions to optimise tree growth and enhance sawing techniques to maximise the production of straight timber. The industry is generally technologically advanced and utilises tools like X-ray scanning, 3D analysis, exterior scanning, and customised sawing (see Fig. 4) to achieve maximum yield (Ursella 2018). However, from the perspective of the industry, only standardised products are interesting because of the current workflows and demands from the building industry. Therefore, high-quality timber still ends up as firewood or pulp due to its non-standard shape. While firewood and pulp can be useful, these applications are short-lasting and thereby an environmental burden.

Hard and valuable wood species like beech and oak easily grows into crooked shapes that do not fit with the current market and industry standards. However, they have excellent properties as construction materials, and there is a historical precedent for handling their irregularities (Andersen 1997). We, therefore, suggest up-cycling of discarded timber through alternative use of already present technology. Using scanning and analysis technology similar to what is being used in modern sawmills, the naturally grown shape of the material itself can be used to inform the construction and machining. The logs can be organised parametrically into constructions or building elements. This has the potential of creating workflows where the properties of the natural wood inform both the architecture, as well as the creation of the architecture.

## 3 Framing the investigations

The processing of wood in its natural form presents (at least) two challenges: one is a technical challenge and the second is an architectural challenge. The first challenge is quite



**Fig. 4** Advanced scanning technology is an integrated part of the wood industry. From left to right: intelligent, semi-automated harvesting, 3D X-ray scanning, and computerised quality analysis

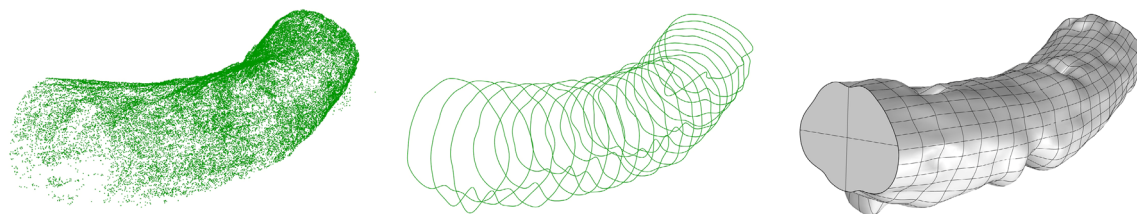


**Fig. 5** Pile of discarded crooked oak logs is inspected and picked up at the sawmill



**Fig. 6** Logs are scanned near the fabrication facilities. A combination of lidar scanning and reference sticks enables the scanning of larger quantities of logs to be scanned directly on the ground without further preparation

tangible, and consists of the techniques and methods needed to handle non-uniform material back and forth between digital and physical space. The second challenge is the more



**Fig. 7** Scanned data are transformed into NURBS geometry, which functions as a lightweight representation of the digital stockpile. The translation is done using a custom script optimised for crooked log:

abstract task of investigation and describing the architectural potentials and relevance of utilising crooked wood in constructions. The two challenges are confronted simultaneously by establishing a series of experiments investigating different types of architectural elements. The element of roof, wall, column, and cladding has been discussed through experimentation, but the task is not delimited by these only. The experiments start to form an architectural language that includes the natural form and the aesthetic value of the original wood.

This paper focuses on the workflow for the roof experiment. For this purpose, a system based on a lamella roof principle is investigated. Existing research on lamella roof principles demonstrates workflows that integrate computational design and robotic fabrication (Tamke et al. 2010) However, these projects make use of standardised timber rather than wood in its natural shape.

The lamella principle allows the construction of large spans using relatively small wood members. Size is important in this specific research setup, since the available robot cell is limited in reach and thereby has a restraint of the length possible to machine. The lamella system allows the analysis and machining of numerous logs within our physical limitations. Furthermore, the lamella system has a direct benefit from the curvature of the logs when used for a construction with an overall curved shape. The phenomena of lamellas' over-shooting joint in highly curved surfaces can be accommodated using curved pieces instead of straight. As such, the lamella roof system represents an excellent scenario for developing and testing tools and workflows for crooked sawlogs.

## 4 Workflow

The following workflow describes the method created for the lamella roof investigations. The workflow is specialised to the task, but also specifies a general strategy for processing of non-uniform sawlogs. The workflow is based on local resource arrangements and available fabrication facilities. By establishing an entirely integrated design-to-production workflow, we attempt to include scalability and methods that

the overall shape of the log is precisely described using simple geometry, without paying attention to smaller surface variations

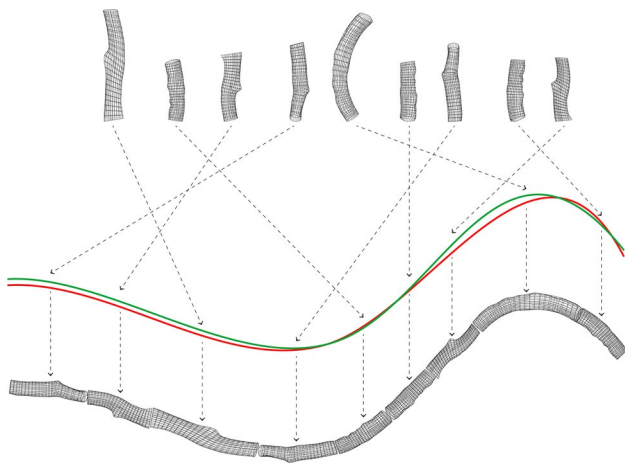
can be relevant in a more professional, industrial setting. This is done using bespoke computational design tools and digital technology for analysis and fabrication. The workflow consists of three phases: stockpile, design, and fabrication.

#### 4.1 Stockpile

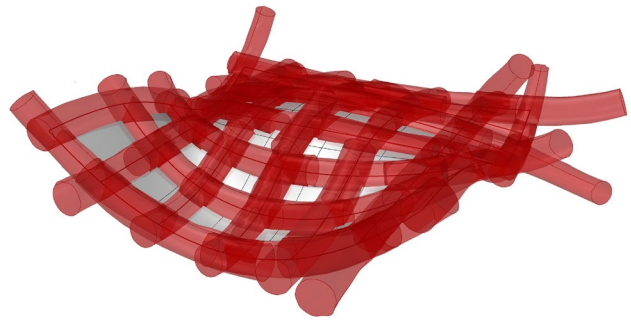
Oak logs are collected from a local sawmill when their stock of discarded logs has reached a suitable amount (see Fig. 5). The logs are both branches and trunks, all too crooked for normal use. After collection, the logs are cut up in lengths appropriate for the subsequent machining. This step is necessary for this specific robot setup, but could be avoided in larger fabrication facilities. The logs are labelled for later referencing, and three red-positioning sticks are mounted for later use. An array of logs is then scanned to get a digital representation of the stockpile.

The digitalisation method has been tested using different types of equipment including Faro Arm laser scanner, photogrammetry, and Faro Focus lidar scanner. For larger quantities, the Focus lidar solution has proven most efficient (see Fig. 6). The scanning has been done mostly with the logs lying on the ground. This practise causes the bottom quarter of the logs not to be scanned, which results in a rough approximation of this part of the logs. So far, this phenomenon has not been problematic, but the more recent scanings are done in an operation where the logs are scanned sitting on sawhorses. This setup allows scanning from both top and bottom and creates a complete point cloud.

The scanning is done near the fabrication facilities. A convenient alternative would be to instead scan the logs at



**Fig. 8** Diagram showing how logs are positioned according to their curvature in the topological relation. An algorithmic dialogue between overall and component geometry is established, allowing both parts to influence the overall design and the precise processing of the components. Green curve illustrates input geometry, while the red curve describes an actual possible solution



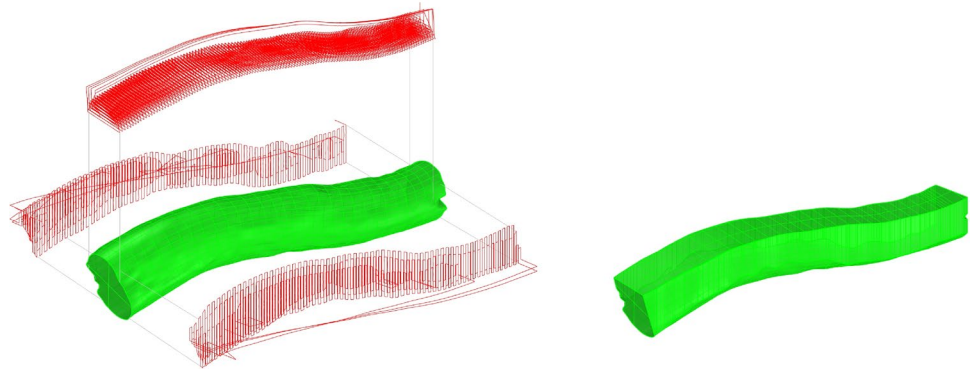
**Fig. 9** Logs from the stockpile populate the input surface. They are placed and rotated to create the best match allowed by the available stock

the sawmill for sourcing logs with specific properties or managing log and data from several sawmills. Even better, the logs would already come with associated digital files from the sawmill. This option would be technically possible and only requires partnership with a modern, co-operative sawmill. Unfortunately, such an arrangement has not been possible yet. Such a partnership would be beneficial not only because of convenience but also because of the data type. Since many sawmills use X-ray or CT scanning, such a collaboration could also impart interior scanning. X-ray and CT scanning have been utilised in this project, but since this type of equipment is not available daily, the workflow currently relies on exterior scanning. Having only exterior scanning does impact the workflow, design, and machining. The current scanning offers a good description of the surface. However, often, the surface is covered with bark, moss, and fungi. An interior scanning would allow the workflow to look behind these covering layers and acquire more accurate information on the wood surface. An exterior scanning would also give information on internal cracks and knots,



**Fig. 10** A band saw on a six-axis robot arm is trimming the curved sawlog

**Fig. 11** For each sawlog, a set of toolpaths are generated



and let the analysis determine the shift from sapwood to heartwood. The later is especially important when determining the depth of machining and positioning of joints, as the heartwood of oak is extremely strong and long-lasting, and the sapwood is just the opposite. At the moment, these challenges are overcome with general approximation. The ambition is, however, to introduce interior scanings to the workflow at a later stage.

The point clouds are highly accurate and consist of thousands of points. Because of their heaviness, they need to be processed before further work is done. This is done in Grasshopper for Rhino using a combination of standard components, Volvox-plugin components, and custom Python script components.

The scan data are cropped into individual point clouds for each log, and for each log, the reference sticks are located using an RGB filter. The point clouds are subsampled and sectioned. Through an iterative process, a custom script finds the centre curve for each log. Following that, another script selects a number of points from the sectioned point clouds with an even distribution around the centre curve. For each end of the logs, the script used extracted planes to located points aligned to the log-end orientation. The selected points are interpolated into curves, and the combination of end

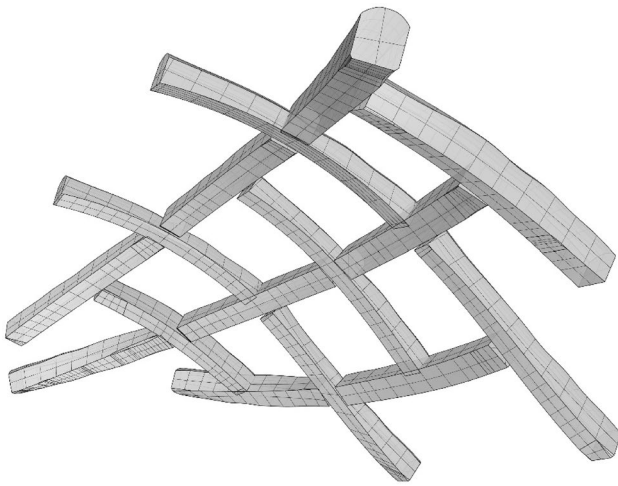
planes and curvatures constructs closed NURBS polysurface (see Fig. 7). The data set now consists of both the original point cloud, centre curvature, skeleton lines, and NURBS surface, as well as the locations of the red-positioning sticks and labelling. The data sets now become a digital stockpile of the available logs. The stockpile functions as an amassing of resources that can dynamically shrink or grow. At



**Fig. 13** Two curved logs joined into a lamella sub-element. The two logs are machined to both accommodate their natural curvature and form a continuous surface together

**Fig. 12** Orientation of the sawlog is located using an OptiTrack motion capture system. Three positioning points are probed using a custom probe tool. Tool paths are reoriented to match the placement of the sawlog





**Fig. 14** 3D model of a in-progress scaled-up demonstrator with several logs. The logs have individual parameters but together form a cohesive structure

any time, the digital stockpile can be reached, and available resources assigned to a design.

## 4.2 Design

Ideally, both internal structural principles and the outer shapes of the logs are reflected in the design choices. Therefore, this experiment tries to preserve fibre directionality and minimise broken fibres to maintain both natural strength and mode of expression. The fitting of the logs into a larger constellation must, therefore, be a negotiation between the available stock material and architectural design intent (see Fig. 8).

The overall geometry of the architectural design is defined as an NURBS surface serving as a reference for the following distribution of the logs. At the moment double-curved, rectangular single surfaces are used, but the system could easily be expanded to include the other shapes and poly-surfaces. Through a series of steps, a custom-made Python script searches through the digital stockpile and proposes matches for the input surface. This part of the workflow is also based on Grasshopper for Rhino, but mainly relying on the custom Python script specifically developed and optimised for this purpose.

The first step of the algorithm is to subdivide the control surface according to preselected dimensions. The resulting isocurves are divided into curve segments, each defining a structural member in the lamella roof system. The next step is to pair each member with a suitable log from the pile. For each member, the curvature of the segment is compared with the available stockpile, and the log with a centre curve that deviates least from the isocurve is selected. The digital representation of the log is placed on the surface and rotated

to match the surface segment as optimally as possible (see Fig. 9). The precision of the overall result depends on the stockpile. A small stockpile will typically result in less good results. So far, it is the experience that the available sawlogs have quite diverse curviness. However, a stockpile with a very even type of curviness on all logs could also provide less good matches. In the testing of the workflow and algorithms, both real stockpiles and augmented stockpiles have been used; the latter especially to test the robustness of the scripts on larger surfaces.

The result is a structure where the available stock matches the overall design as closely as possible, while the logs maintain their original curvature. The algorithm produces a virtual model consisting of components produced from the available stockpile, rather than an abstract model of ideal components. In this way, the resulting design represents a negotiation between design intent and the shapes of the natural materials. In the basis workflow, the algorithm prioritises the matching of the most curved parts on the surface first. The script can, however, be configured to prioritise other aspects. This could, for instance, be an edge condition, a certain area, or a specific section through the surface that needs low deviation. Thereby, the workflow can be adjusted to accommodate specific architectural needs or simply to produce multiple solutions by creating result for a series of different priorities. One could imagine that these options would allow an interface where the architect can provide information to the systems and try out different designs before choosing the preferred combination of the overall design, topology, and available stock material.

The current workflow uses logs of the approximately same size and matches these with curve segments that also have limited variation in length. However, the system could be developed to locate log partitions within longer saw logs or even living trees and match these with construction members that also display larger variation than in the lamella roof construction.

## 4.3 Fabrication

The fabrication is done using a six-axes ABB industrial robot with different available tools. The robot setup provides high freedom, precise control of the machined surfaces and is deeply integrated with the design. The toolpaths and robot code are generated directly from the digital geometry and pairs uniquely with each sawlog.

The available tools are chainsaw, bandsaw, and spindle. The chainsaw is a slightly converted standard, electrical chainsaw. This tool allows for plunging directly into the wood and is good for rough cuts. The tolerance is around  $\pm 5$  mm. The bandsaw is home build and has a quite good tolerance of approximately  $\pm 1$  mm, but is limited to following ruled surfaces (see Fig. 10). The spindle is a standard tool and can be mounted with any router bit needed. The

spindle allows for excellent precision and is, therefore, good for milling of joints. Each tool comes with a custom-made digital tool package that allows us to apply the tools to the selected design. Custom Grasshopper routines for extracting toolpaths specifically for sawlogs have been created. These routines take the fibre direction and shapes of the sawlog into account, and result in a good balance between cutting quality and speed.

The machining of the logs is informed by the design. The logs are machined on three sides, leaving the bottom available for mounting as well as preserving a degree of natural aesthetic. The reason for machining the sides are twofold. First, with a construction of round natural-shaped sawlogs, it is difficult to visually understand the relation between sawlog and design. By trimming the logs, the architectural expression becomes clearer. Second, the machining removes most of the sapwood from the logs leaving mainly the construction-grade heartwood. Due to high moist and nutrition content, the sapwood would decompose over time and is, therefore, always left out of oak constructions.

The two sides are machined as parallel-ruled surfaces directly informed by the original centre curve of each log. Toolpaths for either bandsaw or spindle can easily be generated. The third side is more challenging as it describes the overall design, but is never matched totally by the stockpile. Therefore, a new surface is generated based on the actual, chosen, and positioned sawlogs. The new surface is interpolated through an offset of the log centre curves with a special attention made in any joining situation. The surface used for the final machining is, therefore, created as a result of the dialogue between original surface and available logs. For each sawlog, a set of toolpaths are generated (see Fig. 11).

Just before the robot code is executed, the actual oak log is brought into a position that respects the robot setup's machining limits. The robot cell is equipped with an OptiTrack motion capture setup that is used to determine the position of the logs by probing and matching of the red-positioning stick both found in the digital data set and on the actual log. The probing is a lightweight method that allows fast localisation of the logs and instant 3D reorientation of the tool paths. A custom-made Grasshopper plugin allows direct fetching of planes from the OptiTrack motion capture system. As soon as the reference planes are available, the robot targets are reoriented within their work object to match reality (see Fig. 12).

Each log is machined to have joint details in the ends and on the sides (see Fig. 13). When assembled, the machined logs form a continuous surface both respecting the design intent and original shape of the log.

## 5 Conclusion and further research

This paper displays and describes a workflow for utilising crooked oak logs in construction systems. While the agenda and proposition are to be seen as a thematic discussion and a critique of the current way wood is handled and used by the industry, the workflow description is quite concrete. As such, the contribution of the paper is partly as a document for instructive or polemic discussion and partly as direct source for methods to handle the topic in question.

The developed workflow enables a close negotiation between material properties, design intent, fabrication process, and the realised result. The workflow consists of newly developed algorithms and methods to facilitate the steps from handling of raw, natural sawlogs to digitisation, data handling, analyses, distribution, registration procedure, and robotic fabrication. Actual methods are developed, demonstrated, and evaluated for each step. The work stands on the shoulders of others, but brings new ideas and procedures forward. While being highly specific to the designated workflow and still needing refinement, various described developments have already been shared among fellow researchers.

The current state of the research shows promising results, but still needs further development and testing.

First, the use of exterior scanning instead of interior precludes enormous potential. Access to interior scanning equipment is currently problematic, but data sets from interior scanings of full logs have been obtained. It is the ambition to develop a version of the workflow that utilises the interior information for each log. This would allow more control of the final results and even better integrations with the existing high-tech wood industry.

Second, the physical testing of the workflow must be scaled up. The current testing is performed on several iterations and versions of stockpiles but limited to smaller, human-sized sub-elements. To fully demonstrate the workflow, larger, more building-mimicking demonstrators should be made. This part is currently in progress, and hopefully, a suitable site for a larger construction can be disclosed soon. The ambition is to create a span that is big enough to test the architectural potential of the shown concept. A large enough amount of logs is to be able to form a readable surface while still communicating their individual reality of being crooked sawlogs (see Fig. 14). This part of the research is seen as an important next step and as having potentials for intensive development of the current workflow.



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