Laser Scanning with Industrial Robot Arm for Raw-wood Fabrication

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Abstract -

This paper presents an integrated raw-wood fabrication workflow using an industrial robot arm and a laser scanner. The research is situated in a Swiss mountain forestry context where timber in its natural form could be applied locally without relying on large centralized timber industries. While local saw-mills relies on the standard processing tools to transform raw-wood into regular beams and boards, an automated robotic application could exploit timber in its natural form directly for construction. The research proposes a digital fabrication workflow that links industrial robot arm and laser scanning to adapt timber joinery tool-paths to irregular raw-wood such as straight, bent and forked tree trunks. The application employs ABB IRB6400 robot and Faro Focus S150 laser scanner. Several methods are developed for the point-cloud processing including flat-cut sectioning, mesh reconstruction and cylinder fitting. The methodology is tested in two stages: a) scanning a set of tree trunks b) continuous integration within robotic fabrication. The findings compare the scanning method in regards to calibration, pointcloud processing, time needed to communicate between the robot controller, the accuracy of the application. The results show that is possible to perform robotic cutting and scanning interchangeably and the speed of the scanning application is proportionally fast (3-4 min) considering the overall robotic cutting time (60-90 min) depending on the study case.

Keywords -

Laser Scanning; Industrial Robot; Robotic Fabrication; Unprocessed Timber; Raw-wood; Round-wood

1 Introduction

Timber as a construction material is commonly unified into engineered timber products such as panels, boards and beams of regular sections [1, 2]. However, these techniques could be avoided by employing machining tools that help to transform raw-wood into a building material with a minimal processing time. CNC and robotic arms can have a computer-vision, cutting and assembly techniques to adapt to the irregularity of the tree shapes [3, 4, 5].

The scanning methods of timber are applied in sawmills, ranging from fast laser scanners [6, 7] to volumetric CT scans [8, 9, 10]. In the industrial context, the geometry acquisition is used to optimize the cutting pattern of trees into boards, identify timber knots and disregard crooked timber. The process is often well structured using a digital data-base to track the maximum use of material, its age, species, and location where the wood is harvested from [11]. This data is applied only at the scale of the saw-mill companies and is not transferred for a design use.

The introduction of industrial robots arms in the architectural research environments helped to change the notion of a standardized-timber and apply its original form for construction. There is a series of scanning methods that gives a vision to the industrial fabrication methods and informs design decisions such as manual measurement, markers and tracking devices, photogrammetry, camera sensors, laser scanning, virtual reality applications, and volumetric scanning.

1.1 Manual Measurement

Trees are primarily inspected using manual measurement tools and selected based on physical dimensions needed [5, 12, 3, 4]. The selection criteria depends on a geometrical data: length, radial parameters i.e. axis and diameter, curvature, and topology i.e. straight, bent, bifurcated tree trunks. The fabrication process could also be assisted by a visual measurement employing a teach-pendant when coordinates are transferred to a digital model [13]. For example, 3 points could be taken to visualize an end of a beam in a form of circle fitting.

1.2 Markers and Tracking

The marker-tracking system is a lightweight geometric method that allows a fast positioning of an irregular tree trunk. Markers or positioning points could ease the fabrication process if a 3d scan has already been performed. There are several possible solutions to position a log within a fabrication setup: (i) aligning two point-clouds by targets captured during a design stage (ii) pre-drilling dowel holes that match a machining setup [4] (iii) employing point tracking system i.e. (OptiTrack) [11]. The reference of markers is determined by probing and matching reference features both found in a digital data-set and the actual raw-woods.

1.3 Photogrammetry

Digital models of raw-trees could also be obtained by taking multiple photos with a low-cost camera [5]. The process requires a slow post-processing technique to translate the photos‘pixel-data to a point-cloud or mesh repre-

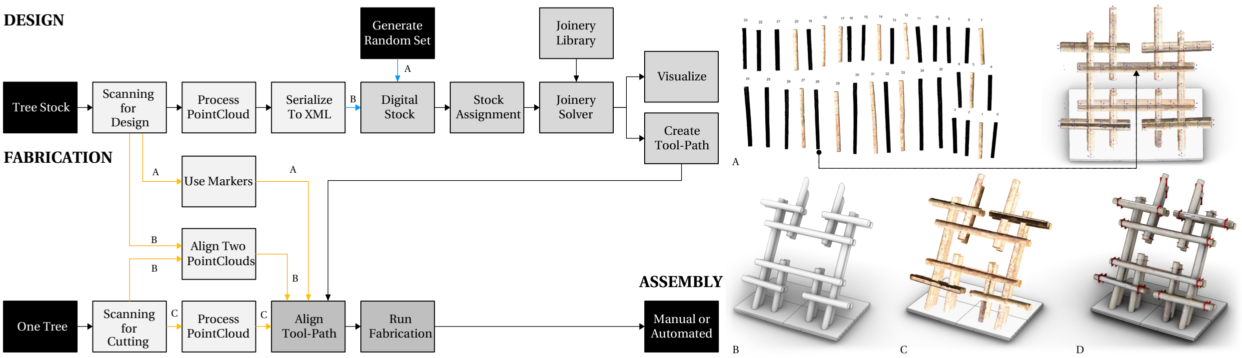

Figure 1. The workflow focusing on design-to-fabrication methods (left). Design method (right) of raw-wood assignment (A) to a digital model (B) that is adjusted for fabrication considering trees radial parameters (C-D).

sentation. The scanning could be combined with a photographic selection and 2D post-processing technique [14] for a large set of forks and only scanning trees that are chosen for a fabrication [4]. When a scanned object is relatively small i.e. tree branches, a rotary table, cylindrical supports, camera, and AR markers could be employed [13, 15]. This is an inverse application when a camera is stationary and the object is rotated in small increments to get a 3d representation.

1.4 Camera Sensors

Camera sensors often employ structured light techniques by projecting a known light pattern to an object [16]. The deformation of the pattern relates to a calculation of depth and surface information in a scene. In a raw-wood context, the most common application is a Kinect sensor [12, 17, 18] due to low-cost and open-source SDK. The technique is subject to light conditions and may require scanning to be performed indoors [12] for a better registration process.

1.5 Laser Scanning

The method combines controlled steering of laser beams with a laser range-finder. Due to the high speed of light, this technique is not appropriate for high precision sub-millimeter measurements, where triangulation and other techniques are often used. This technology has already been successfully applied to scan parcels of forest in Kielder Water and Forest Park (UK) by ScanLAB [19] and a forest in Each Sussex by Universal Assembly Unit. Also, laser scanning could be used for analyzing tree biomass regardless of noise data added by small tree branches [20, 21, 22]. There are several raw-wood applications employing the laser-scanning method for fabrication as well. The method is used with a motion tracking system to guide the raw-wood manufacturing process [11].

1.6 Point-cloud Processing

After the scanning process is finished a skeleton extraction has to be performed to change a high-resolution model to a minimal 3d representation. The tree central-axis and radial-parameters are key elements both for visualization and fabrication. These parameters could be obtained by sectioning a closed mesh [4], 2D projection method following local radii [13], contouring [15], point-cloud sectioning [11]. Then the centers of the sections of the scan are connected to form a central-axis. The axis is used for orientation transformation in design-to-fabrication workflows Figure 1 by analyzing the curvature or topology of a tree trunk. When the geometrical data is collected, a tree database could be constructed containing 3D models and a spreadsheet of tapering diameters, changing curvature, best sawing positions, and markers for positioning.

2 Context and Objective

2.1 Contribution of the Study

While automation in scanning applications and robotic controllers is a well studied field and there are readily available commercial products that could collect the scanning data in real-time i.e MetraScan, Artec RoboticScan, Hexagon, Sick, there is a lack of integration in the raw-wood fabrication and timber design. In the research applications (sections 1.1 - 1.6) the process is based on manual point-cloud processing and the scanning is separated from the robotic control. Commercial practices in raw-wood construction make use of the standardized fabrication that requires a minimal skilled labour to complete the projects by local workers such as Unilog / TTT (New Zealand) and FEEL (Japan). Crooked timber is applied in practice as well i.e. WholeTrees with manual carpentry and stationary scanning i.e. Faro Focus. Moreover, raw-wood could be machined using robot cells i.e. Balmer Systems (Canada) along with scanning Mobic SA (Belgium). A collaboration is built with the later enterprise to employ a scanning application with a robot controller[23] that could gather pointclouds within 4-5 min. using linear movements of a robot for a tree in 5 - 10 m length and diameter of 40-70 cm. The hardware could be optimized further using high-precision and long-range stationary scanners i.e. Faro Focus S 150 and applying a faster communication between a robot controller and the scanner. However, there is a lack of reliable point-cloud processing tools for crooked wood because the current practices do not consider such timber as a valuable resource. Consequently, there is a minimal development of the machining tool-path integration. Small radius straight, tapered, bent and forked beams has a strong structural advantage and could be exploited while developing and automating the workflow between architectural design, digital fabrication and tree harvesting.

2.2 Mountain Forestry

The tree harvesting process is assisted by a collaboration with a mountain forestry in Rossiniere and Lausanne. The Spruce trees are harvested in the Swiss Alps using a cable system due to a high terrain, then brought to a temporary processing site where trees are cut to 5 meters length for the transportation and saw-mill processing Figure 2. In the Swiss forestry context, the raw-wood economic value no longer covers the harvesting costs. Therefore, there is a need to exploit timber in a closed circular economy where wood is not sold to large sawmills but applied locally. Currently, the sawmills rely on the traditional cutting tools and the digital fabrication workflow is absent.

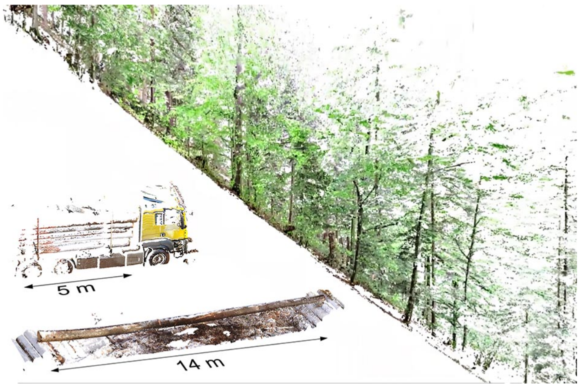

Figure 2. Scans showing a local mountain forestry context: a high and steep terrain where large Spruce trees are cut to fit to a small truck size for transportation to neighbour sawmills.

2.3 Raw-wood Workflow

The research employs ABB IRB6400 industrial robot arm and Faro Focus S150 stationary laser scanner. The scanning of whole-timber is part of a design-to-fabrication system including a laser-scanning, joinery solver, and fabrication techniques for the assembly of irregular timber elements in circular sections Figure 1. The objective is to scan the raw-wood for a design and fabrication using an automatic tool-changer that enables to perform different tasks interchangeably such as scanning, vacuum-grip, and cutting (mill, saw-blade) Figure 3. The scanning is needed because the orientation and position of the work-piece is not known in relation to machining-space. Also, the geometry acquisition is needed for a design scope when a group of selected trees are scanned to create a digital stock. The stock informs the design target - a structural roof system when central-axes of the tree trunks are assigned to a digital model. Afterwards, the timber joints are created depending on a curvature of a beam axis-and radii. Consequently, the fabrication tool-paths are oriented to machining space.

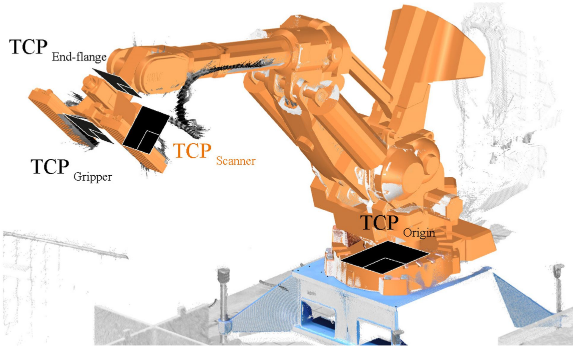

Figure 3. A laser scanner is mounted on a robot vacuum gripper and the $TCP_{Scanner}$ is not known.

3 Methods

The methodology focuses on a scanning application to automate a stationary laser scanner that can be used both for scanning parcels of forest and employed in a digital fabrication. The data acquisition is composed of following parts: physical setup of a scanner mounted on the robot, calibration of the scanner to know the relative position to the robot end-axis, standalone application of the Faro LS 150 SDK (software development kit), its integration within the robot control software (Rhino, Unity), point-cloud processing to obtain radial parameters of harvested timber, serializing data for further design and tool-path alignment for cutting Figure 1.

3.1 Setup of Industrial Robot Arm

The scanner is mounted on a vacuum gripper Figure 4 for safety reasons. The communication between the scanner and computer is enabled by a wi-fi. Then the SDK is applied and .NET application is made to send and retrieve signals from a scanner. The application could trigger following methods: connection, synchronization of scanning parameters, start, pause and stop scanning, send and read data. The power is supplied by 5 hour lasting batteries or a 19 V cable. The files are stored inside SD card that could be sent to computer via the robot-controller. The field-of-view of the scanner is 0° × 360° in the horizontal and -150° × 150° in a vertical rotation.

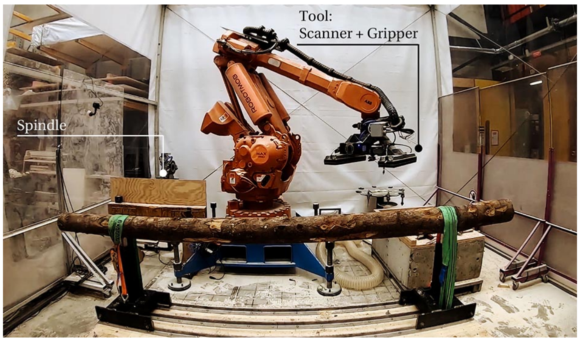

Figure 4. Laser scanner is positioned on a vacuum gripper. When the scan is finished the tool is automatically changed to the spindle

The raw-wood mounting setup is built as a rail-system that has three reference points. The rails are made from L-shape profiles that are fixed to stands to hold a tree trunk. Four steel Y-beams ensures the stability of the setup. Two parallel stands are used for a straight beam fixation and a third one is employed for forks. A beam is fixed to the setup by straps and pre-drilled holes helps to reduce a rotation during the fixation Figure 4.

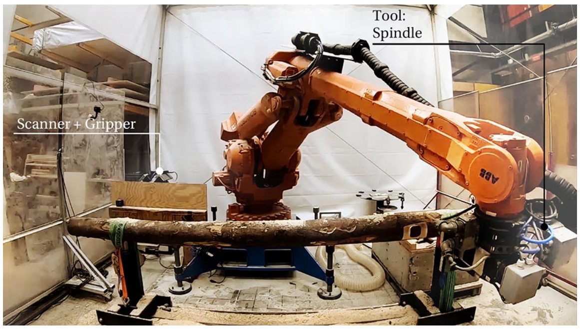

Figure 5. Cutting process using spindle and milling while the scanner and gripper is removed.

3.2 Control of Robot and Laser Scanner

The robot control is based on a software interoperability between the CAD/CAM application (Rhinoceros) and the cross-platform game engine (Unity). One software is utilized for geometry processing algorithms that could be applied to define the robot tool-path while the other is used to simulate the robot‘s movements physically and digitally. Each software has different coordinate systems that has to be matched to get an exact representation. The notation of rotation (Quaternion) and position (XYZ) is translated as following R_{ABCD} to R_{BDC-A} and T_{XYZ} to T_{XZY}. The match between two coordinate systems is found by computing all possible permutations for rotations and positions. The text interface with a robot controller enables to move robot in absolute and linear movements, change tools and tool-holders, perform scans, retrieve and process pointclouds. The cutting process is connected within a design-scanning workflow where a series of fabrication tool-paths are generated considering saw-blade cutting, milling and drilling. Each scan is triggered when the robot reaches a target and then the next pose is taken when the scan is finished.

3.3 Calibration of Laser Scanner

The laser scanner has to be calibrated in relation to the end-axis of the robot to know a pointcloud location at each scan. This process helps to avoid point-cloud processing and registration because the position of the scanner is already known in the robot world space Figure 6. The unknown (1) is a transformation matrix X of a scanner TCP_S that is relative to the end of the robot 6th axis TCP_R.

$$TCP_S = TCP_R + X \tag{1}$$

When a scanner is calibrated, a list of scan points P_i in a world-space is found by multiplying the rotation matrix XR_R^W and the translation matrix XT_R^W of the robot in the world space with points p_i that are positioned relative to the scanner rotation XR_S^R and position XT_S^R that is mounted on the robot arm (2).

$$P_i = XR_R^W * (XR_S^R * p_i + XT_S^R) + XT_R^W \tag{2}$$

While the robot and laser scanner is fixed, a calibration accuracy limits the alignment of scans (3). Several calibration methods were applied including: (a) the multi-scan registration on a sphere, (b) alignment to a robot base, (c) employing an external scanner device and (d) sharp tool manual reference, (e) 4TCP method for the scanner holder measurement. The precision T of the scanning technique depends on a scanner tolerance T_S (±0.1-0.5), marker detection precision T_M, robot accuracy T_R (±0.5-1.0), a calibration method precision T_C (3).

$$T = T_S + T_M + T_R + T_C \tag{3}$$

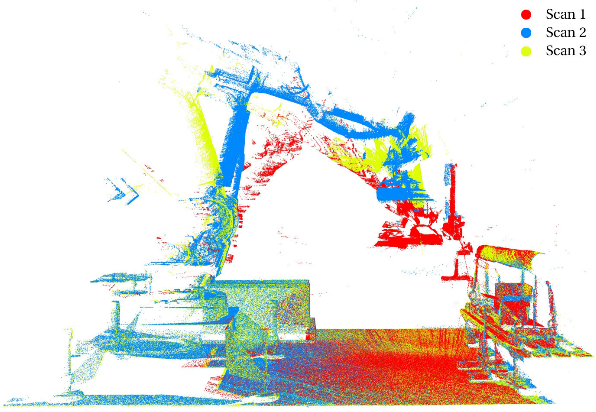

Figure 6. Result of the calibration using Faro Focus S 150 laser scanner.

3.3.1 External Scanner Device

First calibration test was made by employing Faro Arm Figure 7 D to measure the end-flange of the robot and laser-scanner. The result was inaccurate and only gave an approximate position of the scanner. The imprecision varied between ±1.0-2.0 cm in translation and ±1.0° in an arbitrary rotation. While the Faro Arm is a precise measurement tool, the reflective surfaces and possible laser-scanner tilt in relation to the tool-holder could have resulted in such a high inaccuracy.

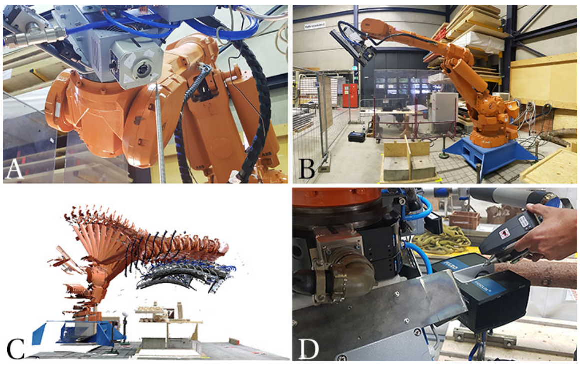

Figure 7. Calibration methods. A - 4TCP Toolfolder, B - Robot-base scan, C - Multiple scans on a sphere, D - Faro Arm

3.3.2 Reference Points

A reference point calibration using an engraver tool and checkerboard markers proved to gain a sufficient tolerance. Robot is moved manually using the Teach Pendant to the centre of each target within several tries. The tolerance of manual measurement ranges between ±0.25-0.75 mm. Then the robot is moved to the highest reachable position and the scan signal is triggered from the robot controller. When the scan is finished, the data is sent to computer where it is processed to detect the positions of the markers. The scan position is oriented by a plane-to-plane transformation. The plane of the measured points is defined from 4 points and the target plane is retrieved from the detected markers. Four planes are created from the points, that are averaged by planes‘ origins and axes to obtain a better fit. The same procedure was tested using 12 targets to increase the tolerance. The resulting precision is between ±1.5-2.0 mm which is good enough for detecting the raw-wood trunk position for the manufacturing of timber joints.

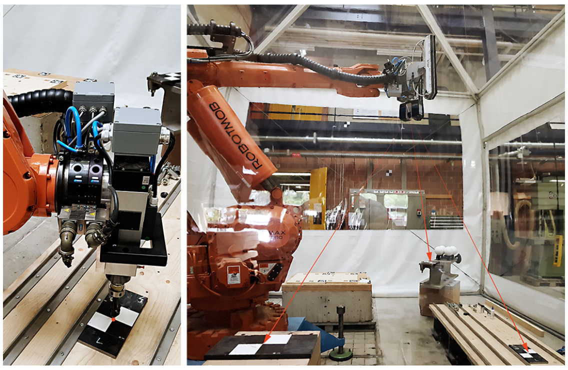

Figure 8. Targets are measured by a sharp-tool and captured by the laser-scanner.

3.4 Point-cloud Processing

When multiple scans are taken and sent to computer, they are processed to obtain the radial parameters and central-axis of the tree. The duration of scanning depends on point-cloud density, measurement accuracy, connection type, the file transfer and geometry processing. The geometry survey could be divided in two parts: (i) creating a tree stock for a design and (ii) a tool-path alignment within the fabrication setup. Three methods were developed to obtain the radial parameters including (i) Flat-cut Sectioning, (ii) Mesh-skeletonization, (iii) Cylinder-fitting.

3.4.1 Flat-cut Sectioning

The method for calculating central-axis and radial-parameters from straight or curved logs is based on a point-cloud sectioning and assumption that every beam has two flat-circular ends Figure 9. The workflow is divided into following parts: get minimal bounding-box of a point-cloud using PCA (Principal-Component-Analysis), get two smallest planes of the bounding-box, find the closest-points within the two planes, perform RANSAC (RANdom-SAmple-Consensus) algorithm to identify the flat-cuts of the beam [24], interpolate planes from the RANSAC, cut the point-cloud by a closest-plane method, fit sections to circles, draw axis between circle centers, serialize the data to XML file. The method will fail if the robot cannot move far enough to obtain he flat cut or the beam is not cut flat on the both ends.

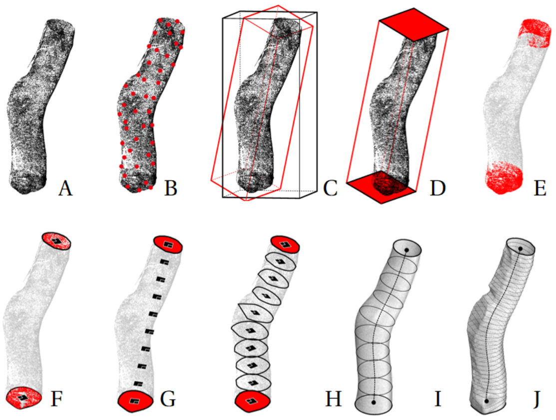

Figure 9. Flat-cut Sectioning method: A - Point-Cloud, B - Sub-sampling, C - PCA, D - two smallest faces, E - closest points, F - RANSAC plane, G - interpolation, H - 2D Convex-hull, I - circle-fit, J - surface representation.

3.4.2 Mesh Reconstruction

The method is based on a surface reconstruction from a point-cloud [25] and the closed mesh skeletonization [26]. Unlike the Flat-cut Sectioning method, it can be applied to the tree forks as well as bent or straight trees. Poisson surface reconstruction is chosen to retrieve a closed mesh from point coordinates and normals. The normals are approximated by fitting points to a plane using a least-square method. Structured point array simplifies the normal estimation because the orientation point (scanner position) is already known. The local radii of a log is found by sectioning the mesh by planes that are tangent to the skeleton-axis. The method is implemented as part of the robotic framework and tested within a series of bifurcated trees Figure 10 G-H.

3.4.3 Cylinder Fitting

The third method employs a cylinder fitting of the point-cloud. The list of points is projected to a 2D plane to approximate an outline of the point-cloud using the Marching Squares algorithm. Afterwards, the axis is extracted from a 2D curve using Zhang-Suen thinning algorithm. Then the axis is projected to the initial list of points by measuring the local radii of axial points. Consequently, cylinders are fit along each line of axis. The method was tested for both bent and bifurcated beams that contained noise from scanning and external objects such as straps of the fabrication setup and robot parts Figure 11.

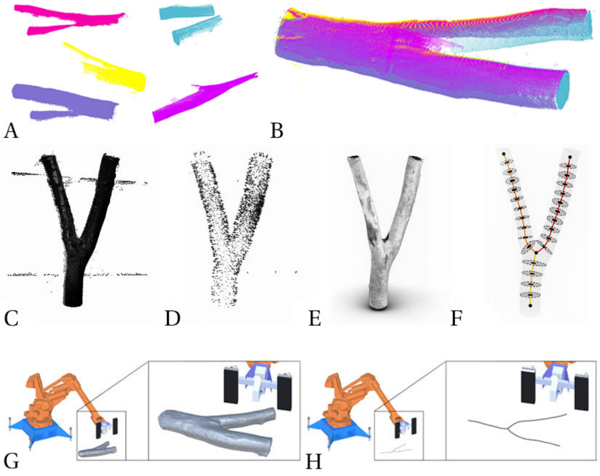

Figure 10. A - Individual Scans, B - Aligned Point-clouds. Mesh Skeletonization method: C - Point-Cloud, D - Normals Estimation, E - Poisson Mesh Reconstruction, F - Mesh-Skeletonization, and implementation in the robotic workflow G - mesh, H - skeleton.

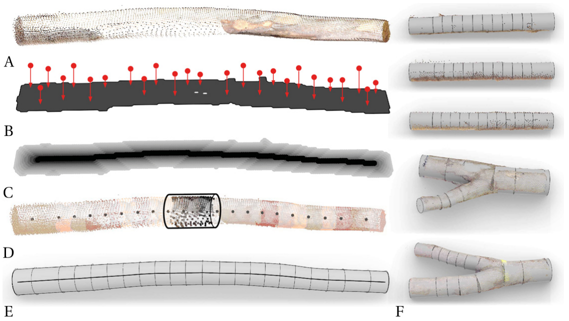

Figure 11. A - PointCloud, B - Projection, C - 2D Thinning, D - Cylinder-fit, E - Radial parameters, F - Application in straight, curved and forked trees.

3.4.4 Fabrication Tool-path Alignment

When the point-cloud is processed, it is serialized for a digital timber stock and machining alignment. While the setup seems almost equal between beams Figure 12, each position changes up to 3-5 cm because of manual positioning, beam properties and rotation during the fixation within an already small radii beam. The minimal model of a scan allows to position the timber joinery following the radius and tangent direction of the axis. There are several ways to reference a digital and analog model such as: a) alignment of a beam to the scanned object before the machining starts Figure 5 b) employing markers that have a distinctive reflective color that are captured during the scanning process.

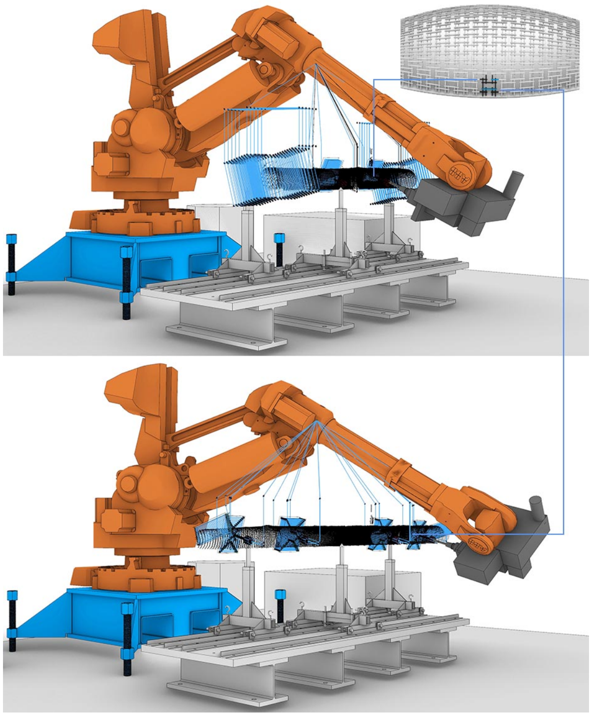

Figure 12. The tool-path is oriented from the design model to the machining space.

3.4.5 Validation Process of Results and Outcomes

The proposed methodology was applied in the realization of a first prototype made from 13-16 cm diameter logs Figure 13. A second one is planned as a tree fork truss to validate other tree topologies. The first model is composed 24 elements. The cylinder-fitting was applied repeatedly before cutting each beam and resulted in the successful model realization even if beams were small, crooked and bent. The scanning application itself is relatively fast in comparison with the milling and saw-blade cutting (60-90 min). Nevertheless the application could be optimized further by controlling the scanner via the automation adapter to send CAM messages and connecting the device with the robot controller to avoid latency in w-lan communication. Furthermore, the helical-scan could be connected with the robot movements to capture the point-cloud data in one step instead of two separate stages.

Figure 13. First prototype in small radius roundwood made using the applied methodology.

4 Discussion

The SDK of the Scanner, software of the robot control and tool-changer allowed to automate the scanning and fabrication workflow. The scanning precision was expected to be higher considering the specifications of the scanner due to the manual calibration, target detection and robot tolerance. Nevertheless, the precision needed to machine the raw-wood is sufficient enough because the imperfection of wood such as branches, chain-saw cuts, cracks is discarded. Multiple point-cloud processing algorithms were tested and the cylinder-fitting method was proved to be the most successful because it works when a point-cloud is incomplete and if there are outliers within the fewer scan taken per one tree. The challenge of the raw-wood integrated workflow is to speed the cutting process which takes the longest time comparing to the scanning and standardized timber products.

5 Conclusions

The laser-scanner and the industrial robot arm made the geometry acquisition of irregular timber faster from 45 min manual process to the 3 min automated solution, including robot movement, scanning and point-cloud processing. 24 beams were scanned without additional manual processing that directly guided the machining process. The scanning method was necessary to get a position of a tree trunk that helped to position cutting tool-paths within ±1.5-2.0 mm tolerance. The prototyping demonstrated the feasibility of the proposed workflow for low value tree trunks harvested from the local forests.

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