

The Mokume Dataset and Inverse Modeling of Solid Wood Textures

MARIA LARSSON, The University of Tokyo, Japan

HODAKA YAMAGUCHI, Gifu Prefectural Research Institute for Human Life Technology, Japan

EHSAN PAJOUHESHGAR, École polytechnique fédérale de Lausanne, EPFL, Switzerland

I-CHAO SHEN, The University of Tokyo, Japan

KENJI TOJO, The University of Tokyo, Japan

CHIA-MING CHANG, The University of Tokyo, Japan

LARS HANSSON, Luleå University of Technology, Sweden and Norwegian University of Science and Technology, Norway

OLOF BROMAN, Luleå University of Technology, Sweden

TAKASHI IJIRI, Shibaura Institute of Technology, Japan

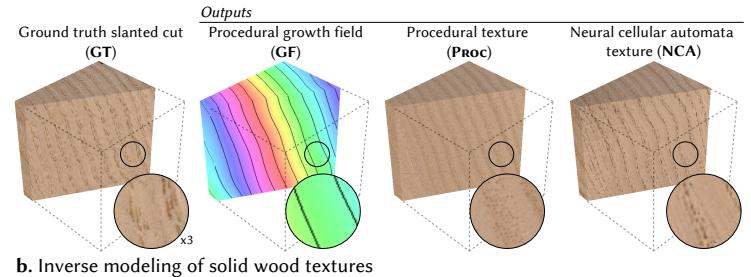
ARIEL SHAMIR, Reichman University, Israel

WENZEL JAKOB, École polytechnique fédérale de Lausanne, EPFL, Switzerland and The University of Tokyo, Japan

TAKEO IGARASHI, The University of Tokyo, Japan



a. The *Mokume* dataset



b. Inverse modeling of solid wood textures

Fig. 1. a. Overview of the diverse wood species covered by the *Mokume* dataset. b. This data is used for inverse modeling of solid wood textures from the exterior cube photographs. Our method first evaluates a neural model that converts the exterior color photographs into 2D annotations of the annual ring pattern. We then use optimization to compute a compatible procedural *growth field* (GF) that assigns a time to every 3D position. The annual-rings are iso-curves/surfaces of this growth field. We showcase two ways to transform this representation into a detailed 3D texture: an efficient inverse procedural model (PROC) with support for point-wise evaluation, and a versatile but resource-intensive neural cellular automaton (NCA).

We present the *Mokume* dataset for solid wood texturing consisting of 190 cube-shaped samples of various hard and softwood species documented by

Authors' addresses: Maria Larsson, ma.ka.larsson@gmail.com, The University of Tokyo, Japan; Hodaka Yamaguchi, yamaguchi-hodaka@rd.pref.gifu.jp, Gifu Prefectural Research Institute for Human Life Technology, Japan; Ehsan Pajouheshgar, ehsan.pajouheshgar@epfl.ch, École polytechnique fédérale de Lausanne, EPFL, Switzerland; I-Chao Shen, jdilyshen@gmail.com, The University of Tokyo, Japan; Kenji Tojo, knjitojo@g.ecc.u-tokyo.ac.jp, The University of Tokyo, Japan; Chia-Ming Chang, info@chiamingchang.com, The University of Tokyo, Japan; Lars Hansson, lars.hansson@ltu.se, Luleå University of Technology, Sweden and Norwegian University of Science and Technology, Norway; Olof Broman, olof.broman@ltu.se, Luleå University of Technology, Sweden; Takashi Ijiri, takashi.ijiri@riken.jp, Shibaura Institute of Technology, Japan; Ariel Shamir, arik@idc.ac.il, Reichman University, Israel; Wenzel Jakob, wenzel.jakob@epfl.ch, École polytechnique fédérale de Lausanne, EPFL, Switzerland and The University of Tokyo, Japan; Takeo Igarashi, takeo@acm.org, The University of Tokyo, Japan.

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high-resolution exterior photographs, annual ring annotations, and volumetric computed tomography (CT) scans. A subset of samples further includes photographs along slanted cuts through the cube for validation purposes.

Using this dataset, we propose a three-stage inverse modeling pipeline to infer solid wood textures using only exterior photographs. Our method begins by evaluating a neural model to localize year rings on the cube face photographs. We then extend these exterior 2D observations into a globally consistent 3D representation by optimizing a procedural growth field using a novel iso-contour loss. Finally, we synthesize a detailed volumetric color texture from the growth field. For this last step, we propose two methods with different efficiency and quality characteristics: a fast inverse procedural texture method, and a neural cellular automaton (NCA). We demonstrate the synergy between the *Mokume* dataset and the proposed algorithms through comprehensive comparisons with unseen captured data. We also provide ablations and quantitative evaluation of individual components of our pipeline. The *Mokume* dataset, our code, and reconstructions are available at www.anonymous-url.org.

CCS Concepts: • Computing methodologies → Volumetric models.

Additional Key Words and Phrases: material texturing, procedural modeling, procedural texturing, neural cellular automata, wood

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1 INTRODUCTION

Wood is an ubiquitous material in real and virtual environments. Natural wood surfaces exhibit mesmerizing textural detail and color variation that impart a sense of warmth and comfort to humans. In this work, we seek to characterize the space of textures originating from the abundance of tree species and the complex relationship between appearance and the angle and position of cuts in wood.

Previous wood datasets imaged localized 2D regions for species identification and tree-ring dating [De Blaere et al. 2023; Fabijańska et al. 2017]. In contrast, the ability to map wood texture onto objects without causing distortions depends on 3D *solid* wood representations that assign an albedo value to positions in space. Comprehensive datasets of this nature are not available, hence prior wood texturing methods have relied on few examples, often unique to each study [Larsson et al. 2022; Liu et al. 2016; Marschner et al. 2005]. We present the *Mokume* dataset to provide this critical ingredient.

Mokume, named after the Japanese word for wood grain, comprises 190 physical cube samples with a side length of 4.0 cm. The samples were taken from 17 different hard- and softwood species, and exhibit diverse anatomical patterns, imperfections, and cut-out placements. Each sample is documented by external surface photographs with annotations of the annual rings, and volumetric computed tomography (CT) scans. A subset of 38 samples were cut to photograph an internal surface for validation purposes. The *Mokume* dataset can support data-driven approaches and enables comprehensive evaluations and robust method comparisons.

Building on this new dataset, we further propose and evaluate an inverse modeling pipeline that infers solid wood textures based on exterior photographs. We address this challenge in three stages: the first localizes 2D annual rings in each input photographs. The resulting information is used in the second step to construct a continuous procedural *growth field* (GF) that maps 3D positions to a scalar value representing the time when the associated material was added during the tree's growth process. This field roughly encodes the distance from the tree's centerline ("pith") and further accounts for distortions due to uneven growth. The annual rings are iso-surfaces of this field. The final step uses the growth field to synthesize solid wood textures.

Unlike previous methods for inverse wood texturing that make assumptions about the location of the pith axis [Lefebvre and Poulin 2000; Nindel et al. 2023], or require manually traced numbered annual rings as inputs [Larsson et al. 2024], our method can directly and robustly infer the growth field from external photographs and annotations of knot centers (if present). We trained a U-Net on the *Mokume* dataset to extract annual rings from the external photographs, to which we fit a volumetric procedural growth field. In addition, unlike forward procedural wood textures that use noise to create distortions [Liu et al. 2016], our model is parameterized by the tree's varying radial growth speed, giving sufficient control to

enable the model to be fit to reference data. Moreover, we propose a differentiable *iso-contour loss* that measures the deviation of growth field values along extracted target annual rings, which is effective for inferring the pith axis and distortions.

With the growth field at hand, we showcase two approaches to synthesize a detailed solid wood texture: an extended procedural model that further accounts for detailed features such as pores and rays, and a neural cellular automaton (NCA) that learns an update rule to iteratively create the desired structure [Mordvintsev et al. 2020]. We optimize both models using style-based losses to produce detailed and realistic textures. The two models occupy opposite quadrants of the quality/efficiency design space and serve to demonstrate the varied applications of the *Mokume* dataset: the procedural model is memory-efficient, editable, and requires a single pass, while the NCA is highly parameter-efficient and can reproduce fine details if significant computation and memory usage are acceptable.

We present qualitative results by reconstructing solid wood textures for each of the 38 samples in our test dataset, comparing the inferred texture of both models to the slanted cuts through the physical cubes. We further evaluate specific components of our framework in a series of quantitative experiments and ablations.

2 RELATED WORK

This section discusses prior work on datasets (Section 2.1), texturing (Section 2.2), and wood modeling and analysis (Section 2.3).

2.1 Datasets

2.1.1 Material appearance. Most prior appearance datasets were curated to support (SV-)BRDF reconstruction of diverse material types such as leather and cloth [Aittala et al. 2015; Henzler et al. 2021; Nielsen et al. 2015]. One notable exception is the work of Marschner et al. [2005], who fit a specialized wood SVBRDF to a dataset comprising five samples. This study focuses on volumetric structure and color, leaving 5D spatio-directional reflectance modeling for future work.

2.1.2 Wood analysis. Various wood datasets cater to applications such as species identification, abnormality detection, and dendrochronological measurement (i.e., tree-ring dating). Datasets for species identification typically include classified optical scans of small patches of end-grain surfaces [De Blaere et al. 2023], tree bark [Warner et al. 2024], or CT scans [Kobayashi et al. 2019]. Another dataset was developed to analyze the effect of surface preparation (the grit of sand paper and type of saw) [Ravindran et al. 2023]. Datasets for abnormality detection are typically made up of labeled images of different surface defects of solid wood or wood veneer, such as knots and cracks [Kodytek et al. 2022; Shi et al. 2020b]. Finally, dendrochronological datasets [Fabijańska et al. 2017; Wu et al. 2023] provide strip images in the outward direction from the pith on cross-section of a stem, often including annual ring annotations.

While the above datasets limit photographs and annotations to localized regions of horizontal cross-sections, the *Mokume* dataset provides comprehensive cross-sectional coverage, capturing all sides of samples taken in various orientations relative to the pith.

2.2 Texture Modeling

2.2.1 Procedural texturing. Procedural texturing, first introduced by Peachey [1985] and Perlin [1985], involves generating a material texture through an algorithmic process rather than referring to explicitly stored data. This approach yields a compact and editable representation capable of producing variations at a low computational cost, and remains a widely used technique. Given these advantages, procedural texturing is particularly suitable for solid textures that exhibit high natural variation, such as wood. The functions for generating various wood features are well understood, owing to Liu et al. [2016], who proposed a comprehensive set of forward functions for generating pores, rays, and light reflections from fiber directions, while others proposed a procedural function for knots [Larsson et al. 2022]. Rather than proposing an improved procedural wood texture model, our target is the inverse problem.

2.2.2 Inverse procedural texturing. While forward procedural methods focus on designing parameters to generate a desired appearance, inverse modeling seeks to automatically discover optimal parameters to ensure that the generated output matches a given target. In computer graphics, this technique has been widely explored; for example, in inverse differentiable rendering [Kato et al. 2020; Li et al. 2018], material or scene parameters are optimized through gradients of the rendering function, enabling tasks such as volumetric material capturing [Gkioulekas et al. 2013], caustic design [Nimier-David et al. 2019], color reproduction [Nindel et al. 2021], and geometric optimization [Liu et al. 2018; Nicolet et al. 2021].

Node-graph representations of procedural shaders, have advanced significantly, evolving from classification or regression for predicting node graph parameters [Hu et al. 2019], later extended to differentiable or semi-differentiable pipelines for material learning [Hu et al. 2022a,b; Li et al. 2023; Shi et al. 2020a]. Beyond parameter fitting, other systems enable generative node graphs [Guerrero et al. 2022] and even prompt-guided searches of these graphs [Hu et al. 2023], achieving near-photorealistic reproduction of diverse materials.

2.2.3 Solid texture synthesis. Creating a solid texture from a 2D reference image is a classical problem [Kopf et al. 2007; Kwatra et al. 2005]. Recent work has extended solid texturing approaches to support inverse modeling through gradient-based learning. Henzler et al. [2020] train a coordinate-to-color mapping (MLP) by feeding multi-frequency noise as input, and Portenier et al. [2020] inject noise into hidden layers for richer outputs. Likewise, Gutierrez et al. [2020] use a 3D CNN that transforms random noise into volumetric textures. However, while these methods focus on synthesizing visually plausible 3D textures from a 2D reference, they do not incorporate wood-specific growth patterns or aim for a faithful volumetric reconstruction. To address this limitation, our approach leverages wood anatomical priors, such as the pith axis and annual ring distortions, to recover the interior of a real wood sample from its external faces.

2.2.4 Neural cellular automata. Neural cellular automata (NCA), proposed by Mordvintsev et al. [2020], are inspired by reaction-diffusion (RD) systems and classical cellular automata (CA), adapting their local update principle while substituting the traditional hand-crafted rule with a small neural network. The model is unrolled

for multiple iterations, and trained end-to-end using backpropagation through time and a style-based loss to synthesize a reference textures. This paradigm is effective for producing self-organizing textures [Niklasson et al. 2021] and has been extended for generating dynamic textures [Pajouheshgar et al. 2023] or texturing 3D meshes directly [Pajouheshgar et al. 2024b], showcasing the flexibility of NCAs in producing complex patterns from simple local rules. This study demonstrates that a natural extension of NCAs to the 3D volumetric setting, combined with our proposed wood-specific priors, is a highly effective model for synthesizing realistic and faithful solid wood textures.

2.3 Wood Modeling and Analysis

2.3.1 Inverse modeling. Two previous studies [Lefebvre and Poulin 2000; Nindel et al. 2023] tackle the backward procedural wood texturing problem specifically, and show a few successful outputs. However, neither handles knots or texture details (pores, rays). They also make severe assumptions about the pith axis location. Specifically, they determine the pith location analytically by identifying the largest orthogonal distance between annual rings, which holds only for a subset of cutout poses. Moreover, [Nindel et al. 2023] extracts contours as a first step, using curved Gabor filters, which, while not requiring training data, is dependent on the image gradient and therefore not robust against diverse wood patterns where features such as rays are superimposed on the annual rings.

Larsson et al. [2024] proposed a learning-based method for inferring a (non-procedural) volumetric texture based on external surface information. Although the problem setup is analogous to ours, there are key technical differences. First, while they require manually tracing numbered contours on the input photographs, we circumvent this requirement by automatic extraction of contours. Second, for global structure inference, they train a model on procedurally generated data (without knots), and optimize the parameters of the trained model, creating a neural growth field. In contrast, we optimize the parameters of a procedural growth field directly, owing to our proposed iso-contour loss. Third, for colored volume synthesis, they independently apply 2D style-transfer on each volume slice, which does not guarantee 3D consistency. Instead, we propose two other approaches: procedural modeling of detailed structures such as fibers, pores, and rays, and synthesizing a color volume using NCA.

2.3.2 Growth field. A growth field representation of wood material analogous to ours was used in previous works, modeled procedurally [Larsson et al. 2022], using a neural model [Larsson et al. 2024], or by evolution over numerous time-steps [Kratt et al. 2015; Mann et al. 2006; Sellier et al. 2011].

2.3.3 Pith detection. Pith detection is a critical task in wood engineering, essential for modeling wood growth patterns to evaluate mechanical properties and optimize material usage. The typical problem addressed involves estimating the pith point in a 2D image captured in a plane roughly perpendicular to the pith axis, whether a photograph of the end of a log [Kurdthongmee and Suwannarat 2019; Norell and Borgefors 2008; Schraml and Uhl 2013] or a CT image of a radial cross-section [Boukadida et al. 2012; Gazo et al.

2020; Longuetaud et al. 2004]. In contrast, we estimate the 3D axis of the pith based on images of external surfaces facing in various directions.

3 WOOD ANATOMY AND TERMINOLOGY

This section presents key terminology to explain and classify key features of wood textures (Figure 2), starting with high-level geometry and moving into small-scale regular patterns. These wood-tissue types introduce distinct color patterns, shapes and arrangements. Their prevalence and visual impact vary by tree species. We further introduce prevalent occasional features, often considered imperfections.

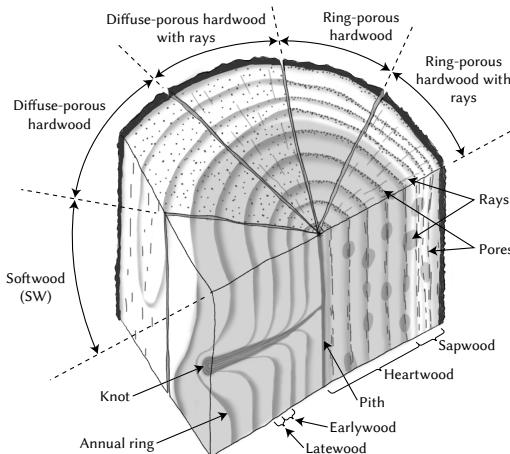


Fig. 2. Terminology of wood features.

- **Pith** is the innermost center skeleton of a tree.
- **Annual rings** are formed by alternating layers of early- and latewood. Earlywood, which grows in spring, appears lighter, while latewood, which forms later in the year, appears darker. This alteration creates a pattern of concentric circles in the radial views and parallel bands in the tangential plane.
- **Pores**, also known as vessels, are tube-like structures extending vertically. Pores appear as tiny circular openings in radial view, and elongated openings in the tangential plane.
- **Rays** are thin, ribbon-like structures extending radially from the wood's pith. Rays are visible as fine lines in a radial view and patch-like dots in the tangential plane.

We identify five categories of wood based on the visibility and arrangement of the above features (see examples in Figure 4). The abbreviations used below are as follows: SW for softwood, HW for hardwood, DP for diffuse-porous, RP for ring-porous, and R for rays:

- **Softwoods (SW)**. The annual rings are typically distinct from the early- and late-wood color contrast, while both pores and rays are indistinct.
- **Diffuse-porous hardwoods (HW-DP)**. Pores are distributed relatively evenly while the annual rings are distinct from the early-to-late-wood color contrast like in softwood.
- **Diffuse-porous hardwoods with rays (HW-DP-R)**. Same as previous but with distinct rays.

- **Ring-porous hardwoods (HW-RP)**. The annual rings are distinct from the pores that follow them, rather than by early-to-latewood color contrast.

- **Ring-porous hardwoods with rays (HW-RP-R)**. Same as previous but with distinct rays.

Finally, there are also non-repetitive features that we term *occasional features* and which are visible in some cut-outs (see examples in Figure 5).

- **Knots**. Darker spots formed where branches once extended.
- **Cracks**. Splits or fissures that typically occur during drying.
- **Insect holes**. Small openings caused by boring insects.
- **Gum**. Resinous deposits that seep from the wood.
- **Heart-to-sapwood color transition**. Heartwood is the older, inner core of the tree that is often darker. Sapwood is the outer, often lighter-colored portion of the tree. We list the heart-to-sapwood color transition under occasional features because it is visible only in some cut-outs (those placed at the border).

4 THE MOKUME DATASET

This section introduces the content of our dataset: the characteristics of the physical samples (Section 4.1) and how they were collected (Section 4.2) and documented (Section 4.3). For implementation details, refer to supplementary materials A.1.

4.1 Physical Samples

The *Mokume* dataset comprises 190 physical wood cubes with a side length of 4.0 cm, which are diverse in terms of species and trees (Section 4.1.1), anatomical features (Section 4.1.2), and cut-out poses (Section 4.1.3).

4.1.1 Species and trees. The samples come from 17 different hard- and softwood species (Table 1). There are 10 samples per species except for the softwoods *Sugi* and *Hinoki*, both are types of cypress, for which we included 20 samples because of the frequent presence of knots, which adds significant variety. To capture diversity within each species, we collected the samples from different trees, obtaining 1–10 samples from a total of 91 unique trees (Table 1).

4.1.2 Anatomical features. Species from five categories of small-scale features combinations (see Section 3) are represented in our dataset (Figure 3-left, Figure 4). Moreover, over a third of the samples (74 of 190) have at least one occasional feature: insect holes, visible heart-to-sapwood transitions, cracks, knots, or gum (Figure 3-right, Figure 5).

4.1.3 Cut-out placements. The appearance of wood changes depending on how the cut is placed. For instance, nearer to the pith (where the growth starts), the annual rings have a relatively stronger curvature. The anisotropic nature and three-dimensional structure of wood cause surface patterns to vary based on the orientation of the cut. To capture these types of diversities, we varied the cut-out *locations*, that is, closer or further from the pith of the tree, and *orientations*, that is, straight or angled in relation to the pith (Figure 6). We estimate the actual cutout locations and orientations by running our pith inference optimization (refer to Section 5.2) on the full dataset based on the annotated annual rings. This analysis reveals many samples are relatively straight and positioned at a

Table 1. Species in the Mokume dataset. N_S is the number of cube samples. N_T is the number unique trees from which the samples were cut.

Code	Name	Scientific Name	N_S	N_T
B	Beech	<i>Fagus spp.</i>	10	10
BW	Black walnut	<i>Juglans nigra</i>	10	10
CH	Cherry	<i>Prunus serotina</i>	10	4
CN	Kuri	<i>Castanea crenata</i>	10	5
H	Hinoki	<i>Chamaecyparis obtusa</i>	20	2
IC	Icho	<i>Ginkgo biloba</i>	10	2
K	Keyaki	<i>Zelkova serrata</i>	10	10
KR	Kurumi	<i>Juglans mandshurica</i>	10	4
MP	Maple	<i>Acer spp.</i>	10	5
MZ	Mizume	<i>Betula grossa</i>	10	5
N	Nara	<i>Quercus crispula</i>	10	10
NR	Nire	<i>Ulmus davidiana</i>	10	7
P	Platanus	<i>Platanus occidentalis</i>	10	1
RO	Red oak	<i>Quercus rubra</i>	10	8
S	Sakura	<i>Prunus spp.</i>	10	4
SG	Sugi	<i>Cryptomeria Japonica</i>	20	2
TC	Tochinoki	<i>Aesculus turbinata</i>	10	2
			190	91

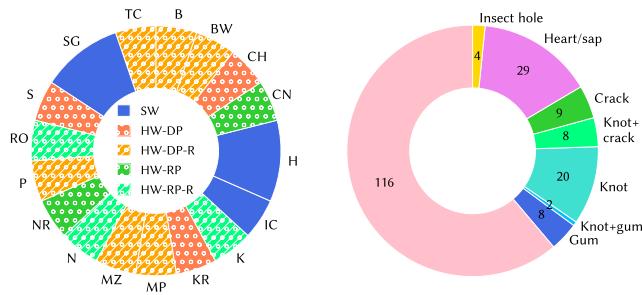


Fig. 3. Left: Species regular pattern categories. Showing the different distributions and combinations of pores and rays for the species in the dataset. Pores are classified according to Murayama and Murayama [2020]. Ray classifications are based on our observations. For category codes, refer to Section 3. **Right: The number of samples with various occasional features.** The counts are based on our observations.

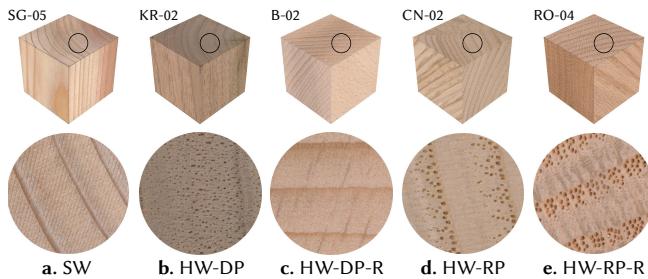


Fig. 4. Samples from species with different regular patterns categories. Note that the pores of B-02 are small and just barely visible.

5-10 cm from the pith. However, cut-out poses vary significantly

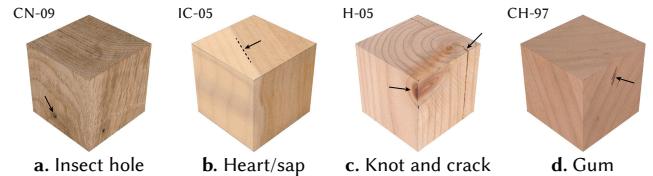


Fig. 5. Samples with various occasional features.

with orientations ranging from 0 to 53 degrees and pith distances ranging from 1.5 to 33 cm. (Figure 7). Pith distances less than 2.0 cm indicate that the pith itself is included in the 4.0 cm cube sample, as the distance is measured from the sample's center.

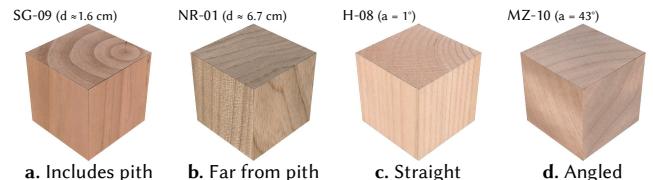


Fig. 6. Samples with various cut-out *locations* (a-b) and *orientations* (c-d).

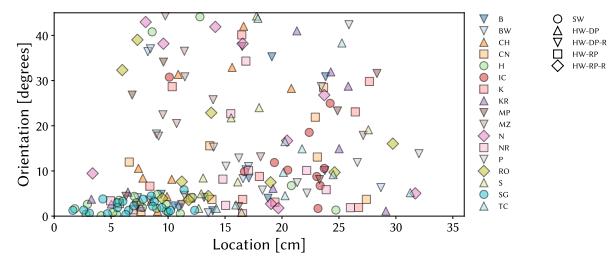


Fig. 7. Estimated cut-out locations and orientations. The x-axis indicates the *location*: the distance between the sample center and its nearest point on the pith axis. The y-axis indicates the *orientation*: the angle between the pith axis and its most closely aligned orthogonal axis.

4.2 Collection and Preparation

Hardware and online stores typically sell unfinished wood cubes from a few common species (e.g., cypress and oak) with minimal variation between specimens. Rather, we sourced dry wood directly from wood mills and cut them into cubes ourselves, enabling a more diverse sample set. The wood mills visited were those cutting wood for furniture production and building, thus using relatively high-grade materials of species likely to be found in interior settings.

We used a table saw to cut the blocks, producing smoother surfaces than a band saw. However, some samples, particularly softwoods, show visible cut marks from the table saw. We did not sand or finish the surfaces due to various possible techniques and available products, which would require a separate extensive study of its own to cover a sufficient range [Ravindran et al. 2023]. We chose a cube side length of 4.0 cm, as it is the largest commonly available thickness, with thicker lumber being rare due to its proneness to cracking when drying.

4.3 Documentation

Here, we introduce the modes of documentation of external and internal information of the wood cubes specimens (Figure 8).

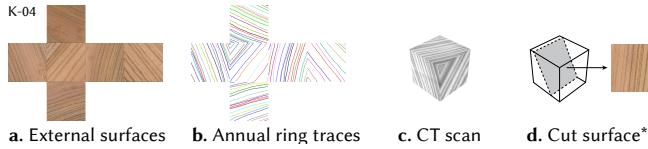


Fig. 8. Dataset documentation overview. *Available for 38 of 190 samples.

4.3.1 External photographs. We obtained photographs of the six sides by scanning them in batches together with a color scale using a high-resolution (1,200 dpi) office desktop 2D scanner (EPSON DS-G20000) (Figure 9). Individual photographs were cropped out from the batch scans, resulting in an image size of approximately 1,880 px \times 1,880 px. There are six external surfaces per cube and 190 samples, giving a total of 1,140 photographs.

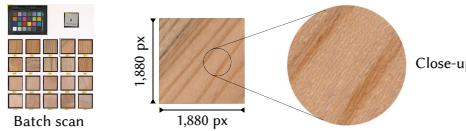


Fig. 9. External surfaces capturing.

4.3.2 Annual ring annotations. For each photograph, we provide manually created annotations in the form of numbered traces of the annual rings. The traces are stored as monochromatic 256² image with integer pixel values representing the year up to an arbitrary global offset. Inside knots, the annual ring annotations are largely left blank because they have highly dense annual rings, which are difficult to annotate in the set resolution. The annotations were created using a drawing interface with a stylus pen and a touch screen, and adds up to a total of 420 m.

4.3.3 CT scans. We also scanned wood samples using a specialized industrial CT scanner for timber (Microtec Mito) to obtain 3D volumes (Figure 8c).¹ Although we do not use them in our own experiments, we include the CT scans to enable future applications requiring additional 3D ground truth data. Each scan approximately covers 128³ voxels of size [.3 mm]³.

4.3.4 Photographs of cut surfaces. After dividing the samples of each species into a training- and testing dataset (refer to Section 5.1), we physically cut the 38 samples of the test dataset and photographed the exposed cut surface to create a ground truth reference for comparison with inferred textures. There are two types of slanted cuts (refer to Supplement A.1.4). We did not perform this documentation on all samples because cutting the samples destroys them, and left as many specimens intact as possible for future experiments.

¹The *Mokume* dataset includes CT scans of all samples except 5 (NR-6 to 10) that were added after the CT scans had been performed.

5 INVERSE MODELING METHOD

Building on the *Mokume* dataset, we propose an inverse modeling pipeline (Figure 10) that infers a volumetric color texture from the external photographs of a wood sample. It comprises three phases: converting photographs into a 2D annual ring localizations (Section 5.1), fitting a volumetric procedural growth field to the extracted localized annual rings (Section 5.2), and synthesizing detailed volumetric color textures (Section 5.3). Only the first phase uses the *Mokume* dataset as training data. For implementation details, refer to the supplementary materials A.2.

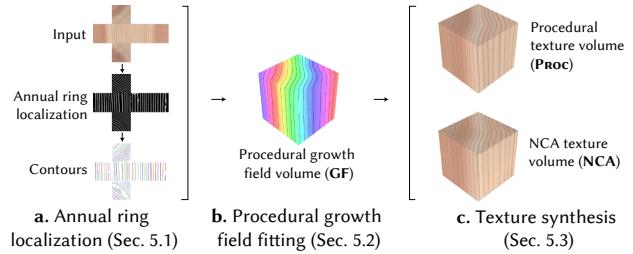


Fig. 10. High-level overview of our reconstruction pipeline.

5.1 2D Annual Ring Localization from Photographs

Annual rings are often subtle and obscured by overlapping features like rays and pores, making their detection in photographs challenging. In particular, standard edge detection alone is insufficient (see Section 6.2.3). Therefore, we approach this as an image-to-image translation problem, converting wood color images into annual ring localization images, enabling more reliable contour extraction (Figure 11).

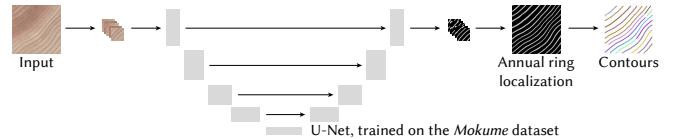


Fig. 11. Overview of the 2D annual ring localization from photographs.

Similar to prior work on annual ring detection [Fabijańska and Danek 2018], we train a U-Net for its ability to recognize image features across different scales. Its input consists of 1cm² patches with resolution 64 \times 64. The details of the network architecture and patch-based training follow Texler et al. [2020]. To further augment the training data and improve generalization to unseen wood samples of potentially different sizes, we augment the data by mirroring, scaling, and transforming the color space of the patches. During inference, we evaluate the network on a sliding window and reconstruct an image by blending the overlapping areas. Additional details on these steps can be found in the supplemental material.

5.1.1 Training data. We use a 80% of the *Mokume* dataset for training. Each training pair consists of an input RGB photo patch and a monochromatic target patch describing the associated annual ring structure. To create this target, we interpolate the hand-annotated

numbered traces (Section 4.3.2) to every pixel to create a fractional 2D growth field g value, to which we assign an intensity value using the following formula:

$$I(g) := (\cos(2\pi g)/2 + 1/2)^{10}. \quad (1)$$

Raising the result to the 10th power sharpens the peaks (annual rings locations). This transformation is invariant to integer shifts², localizes annual rings, and creates smooth oscillatory output (Figure 12). Section 6.2.3 showcases the benefits of this mapping compared to other alternatives. Training minimizes the L_1 loss between the target patches and the U-Net’s output.

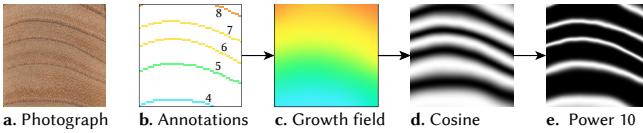


Fig. 12. Training data generation. Each training pair consists of a photo patch and an oscillatory image of the annual ring structure. We create the latter by interpolating integer-valued traces into a fractional 2D growth field that we subsequently transform using a cosine and power function.

5.1.2 Contour detection. The final step applies a threshold followed by a Canny [1986] edge detector. We trim detections at the image border and connect the remainder into sets of contour curves. This process creates two contours surrounding each annual ring, which is not an issue since the next pipeline stage (Section 5.2.2) only depends on them being iso-curves of the growth field.

5.2 Fitting a 3D Procedural Growth Field

In the next pipeline stage, we extend the 2D annual ring localization images and their extracted contours into a 3D procedural growth field. This section introduces the underlying procedural model (Section 5.2.1), loss function (Section 5.2.2), and optimization scheme (Section 5.2.3).

5.2.1 Procedural model. The function $G(\omega, p)$ evaluates the growth field at a 3D position $p \in \mathbb{R}^3$. It further depends on parameters $\omega = [O, V, R]$, where

- the position and direction $O, V \in \mathbb{R}^3$ specify the *pith axis* representing the start of the tree’s radial growth process. This axis establishes a cylindrical coordinate system, in which positions p can alternatively be expressed in terms of their height h , azimuth ϕ , and radius r .
- $R \in \mathbb{R}^{n_h \times n_a \times n_r}$ characterizes *rate of growth* resulting from varying environmental conditions. In particular, the values R_{ijk} discretize the *radial derivative* $\partial/\partial_r G$ of the growth field at n_h heights, n_a azimuths, and n_r radii.

Figure 13 shows the associated geometry.

Integrating R_{ijk} along the r axis starting from the pith yields the actual value of the growth field at each discretization point. We employ trilinear interpolation to evaluate the growth field at other positions and clamp $R_{ijk} < 0$ when optimizing to prevent inversions.

²This is important because the year labels of annual ring traces are only known up to a integer offset.

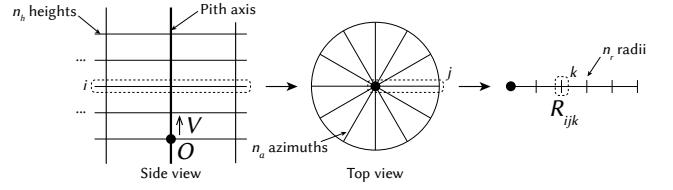


Fig. 13. The role of the growth field parameters $\omega = [O, V, R]$.

5.2.2 Iso-contour loss. The 2D annual ring contours from Section 5.1.2 correspond to iso-contours of the 3D growth field, enabling their use as effective optimization constraints (Figure 14). Given a contour C_i (a set of pixels included in a connected component), we define an *iso-contour loss* that minimizes the variation of values of G along the contour C_i , by minimizing the difference between each point’s value to the average value along the contour:

$$\mathcal{L}_{ic}(\omega, C_i) := \frac{1}{|C_i|} \sum_{p \in C_i} \left| G(\omega, p) - \frac{1}{|C_i|} \sum_{p' \in C_i} G(\omega, p') \right|. \quad (2)$$

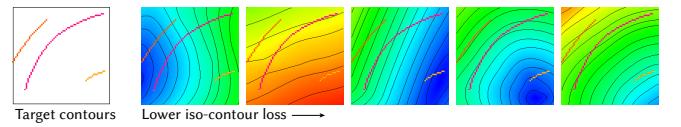


Fig. 14. Iso-contour loss promotes convergence to a 3D growth field, whose level sets on faces align with a prescribed set of target contours.

5.2.3 Optimization. The recovery of the pith axis and annual ring distortions occur in sequence (Figure 15).

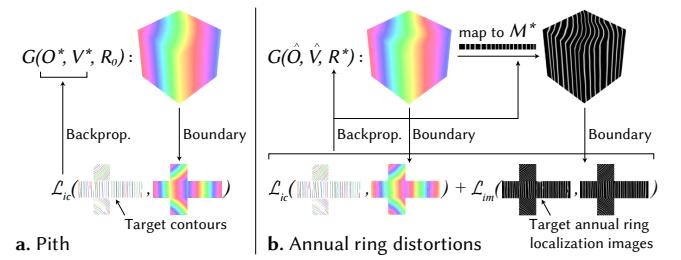


Fig. 15. Procedural growth field fitting overview. Optimization of a) the pith axis (\hat{O}, \hat{V}), and b) the radial growth speeds (\hat{R}) and the gray-map (\hat{M}).

Step 1: pith. We first optimize the pith axis (O and V) of an *undeformed* (i.e., $R_{ijk} \equiv 1$) growth field to find parameters that best match the prescribed set of contours $C = \{C_1, C_2, \dots, C_N\}$. Specifically, we solve the following optimization using a discontinuous coarse grid search followed by continuous gradient-based descent:

$$\hat{O}, \hat{V} = \arg \min_{O, V} \sum_{i=1}^N \mathcal{L}_{ic}([O, V, 1], C_i) \quad (3)$$

Step 2: distortions. Annual rings can be heavily distorted, which the previous step fails to consider. Intuitively, we should be able to reproduce this distortions by optimizing the tree’s spatially varying growth rate R via the loss

$$\mathcal{L}_1(R) = \sum_{i=1}^N \mathcal{L}_{ic}([O, V, R], C_i) \quad (4)$$

While this indeed corrects the iso-contour alignment, does not position annual rings in an absolute sense. One way to recover their position would be to apply the oscillatory mapping I (Equation 1, Figure 12) to generate images that can be compared to the U-net’s output (denoted I_{ref}):

$$\mathcal{L}_2(R) = \|I(G([O, V, R], \boxplus)) - I_{\text{ref}}\|_1, \quad (5)$$

where “ \boxplus ” indicates simultaneous evaluation on all cube faces. However, this constrains annual rings to integer values of G , which we found to be exceedingly challenging to optimize. For example, inserting a new annual ring requires a concerted update of all entries of R to preserve the other ring positions at their integer positions. In practice, we often observe convergence to suboptimal local minima.

Rather, we replace I with a piecewise linear function $M: \mathbb{R} \rightarrow \mathbb{R}$ that assigns a gray value to each growth field value. That parameterized function becomes a part of the optimization:

$$\mathcal{L}'_2(R, M) = \|M(G([O, V, R], \boxplus)) - I_{\text{ref}}\|_1. \quad (6)$$

This indirection makes it possible to place annual rings at arbitrary locations, not limited to integer values of G . We finally optimize a linear combination of both losses

$$\hat{R}, \hat{M} = \arg \min_{R, M} \lambda_1 \mathcal{L}_1(R) + \lambda_2 \mathcal{L}'_2(R, M)$$

The annual ring positions are easy to extract as a post-process by locating global maxima of \hat{M} . Specifically, we apply a threshold and extract the location of the centers of each detected area. The final output comprises the volumetric growth field ($G(\hat{\omega})$) and the iso-curve values ($A \in \mathbb{R}$) of annual rings in the field.

5.2.4 Knots. In the rare case where a sample contains a knot, we introduce an additional parameter set ω_k , detonating the parameters of the growth field of the knot (as opposed to the pith of the stem), and a smoothness parameter $s \in \mathbb{R}$, which controls the shape of the stem-to-knot union. We use Larsson et al. [2022]’s method that evaluates a smooth minimum of growth fields around individual skeleton strands:

$$G_k(\omega, \omega_k, s, p) = \text{smooth_min}(G(\omega, p), G(\omega_k, p), s). \quad (7)$$

To find the optimal parameters $(\hat{\omega}, \hat{\omega}_k, \hat{s})$ of a sample with a knot, we apply the same optimization framework as before (refer to Section 5.2.3) after replacing $G(\omega)$ with $G_k(\omega, \omega_k, s)$. Importantly, $[O_k, V_k] \in \omega_k$ requires a close-to-optimal initialization, which is constructed by manually marking the center points of a knot on the external images. There are typically two center points (the enter and exit points) because a knot typically penetrates through a sample, from which we construct the initial knot axis.

5.3 Synthesizing 3D Color Textures

After inferring the 3D procedural growth field, our next goal is to produce an RGB color volume of the wood texture that matches the appearance of the real wood as closely as possible, including details of the texture such as rays and pores. We apply two different techniques— inference of the parameters of a procedural texture (Section 5.3.1) and NCA (Section 5.3.2). Both techniques use the VGG-based style loss proposed by Kolkkin et al. [2019].

5.3.1 Approach 1: inverse 3D procedural texturing. We introduce a function $F(G(\hat{\omega}), A, \phi)$ that takes the inferred global structure ($G(\hat{\omega})$) and A) and a set of additional parameters (ϕ) as input, and produces a color volume. We model the annual rings, fibers, pores, and rays based on Liu et al. [2016]’s formulation of the wood procedural model, with some simplifications and extensions. In particular, we simplify by not modeling surface depth nor complex light interactions. Furthermore, we model the fiber direction as parallel to the pith axis. The extensions include two color-map parameters (size 64×3) that control the radial-outward color variations of the early- and late-wood areas, respectively, facilitating the inverse modeling of sap-to-hardwood color transitions. For knots, we employ a similar color map. Overall, ϕ includes 436 values (or 639 values with one knot).

To determine the optimal parameter set $\hat{\phi}$, we initialize annual ring colors using a continuous optimization and L1 image loss, then switch to style loss, perform a coarse grid search of fiber, pore, and ray sizes, followed by a continuous optimization of all parameters in ϕ .

5.3.2 Approach 2: 3D neural cellular automata. To generate finer details of the wood texture, we first evaluate the growth field on a $H \times W \times D$ grid of coordinates, giving a growth field tensor G . We then fit an average wood color to each growth field value, using a loss similar to Equation 6, yielding a base color tensor B . Although the base color approximates the reference, it lacks fine details like pores and subtle grains. To recover this missing complexity, we adapt the 2D NCA framework from Pajouheshgar et al. [2024a; 2023] to a 3D volumetric setting and train the NCA to learn a residual to enhance the base color B .

Each cell in our 3D grid of size $H \times W \times D$ maintains a high-dimensional state $S \in \mathbb{R}^{H \times W \times D \times C}$, where the number of channels $C = 12$ in our experiments and the first three channels store the residual RGB color. As wood’s fine details depend strongly on anatomical context such as ring structure, we incorporate wood-specific priors into NCA by concatenating the base color B and growth field G with the cell state S , thereby forming an augmented state tensor. In Section 6.4, we show that conditioning the NCA on B and G strongly boosts synthesis quality; ablations omitting these priors lead to less realistic growth-ring continuity and color variation in the volumetric texture.

Each cell then gathers information from its local $3 \times 3 \times 3$ neighborhood by convolving the augmented state tensor with five fixed 3D convolution kernels: identity, three Sobel filters (approximating spatial gradients $\nabla_x, \nabla_y, \nabla_z$), and a 27-point stencil approximation of the Laplacian operator ∇^2 . This yields a $(5C + 10)$ -dimensional vector for each cell, which is then concatenated with the cell’s 3D

coordinates (x, y, z) to form a $(5C + 13)$ -dimensional input to a multi layered perceptron (MLP) with two layers, which calculates the residual cell state update (Figure 16). By unrolling this update rule for many iterations and applying a VGG-based style loss on the cube’s visible faces, we train the NCA model parameters via backpropagation through time. We adopt the open-source implementation, training strategies, and style-loss functions from Pajouheshgar et al. [2024a].

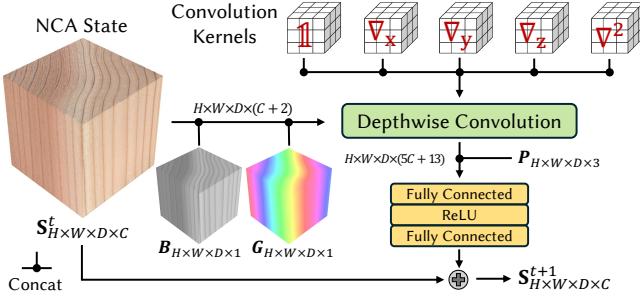


Fig. 16. Overview of 3D NCA architecture for wood texture synthesis.

6 RESULTS

In this section, we show visual outputs of our method compared to ground truth (Section 6.1), and present evaluations of individual components of our pipeline: the structural information extraction (Section 6.2), the global inference (Section 6.3), and the NCA texture synthesis (Section 6.4).

6.1 Qualitative Evaluation of Synthesized Textures

Figures 17–18 present visualizations of the growth-field, and the two texture synthesis methods, comparing performance on a slanted cut through the 38 test samples. Both models often successfully reproduce heart-to-sapwood color transitions (e.g., IC-04) and local color differences (H-14). Furthermore, pore distributions (e.g., CN-01) and ray orientations (e.g., RO-03) are often well reproduced. Owing to its flexibility, the NCA reproduces dense and complex ray patterns for which the procedural model finds a close but not fully satisfactory approximation within its expressivity (e.g., RO-09). The NCA model also reproduces a gum inclusion on the cut surface of MZ-03, though not in the ground truth location, showing its ability to reproduce irregular features beyond that which is included in our (or typically in any) procedural wood model. However, the NCA model does not recognize saw marks as a 2D surface artifact, and partially reproduces them on the cut surface unrealistically (e.g., H-01). When the growth field inference fails, the quality of the synthesized textures suffers, although the NCA shows a relatively better capacity to recover (e.g., N-01).

6.2 2D Annual Ring Localization

In this section, we show the species-wise performance of the annual ring localization image generation (Section 6.2.1) and a generalization test (Section 6.2.2). We also evaluate the accuracy of the edges extracted from the annual ring localization image compared to other methods (Section 6.2.3).

6.2.1 Performance. The image losses of the annual ring localization images vary when comparing different species (Figure 19). Moreover, we observe that the model performs best on the most regular cases when annual rings are distinct and complex patterns are not present (e.g., MP-07-B in Figure 20). The model also typically successfully ignores superimposed visual patterns like sap-to-heart wood borders (e.g., IC-04-B), cut marks (e.g., H-14-D), and distinct rays and pores (e.g., N-01-C in Figure 20). Extremely subtle, barely visible annual rings, however, appear to be more challenging (e.g., S-08-C and TC-04-B in Figure 20).

6.2.2 Generalization test. We conducted an experiment to evaluate the ability of the model to generalize to unseen species. The 17 species were randomly divided into five groups of three species each and one group of two species. For each group, we trained the network on all samples from the species outside the group and evaluated its performance on the unseen species within the group (Figure 21). The median image loss across the six experiments is 0.20, representing a 13.2% increase compared to our standard setting, where the network is trained on 80% of the samples from each species and evaluated on the remaining 20%, which results in a median image loss of 0.17.

6.2.3 Contour extraction. We evaluate the quality of the contours extracted from our generated annual ring localization, and compare it to one ablation and two baselines. The ablation entails omitting the power of 10 in the annual ring localization image construction (refer to Section 5.1.1). The two baselines are extracting contours from 1) a thresholded gray-scale wood photograph directly, 2) a wood photograph after applying a k-means filter ($k = 2$) [Lloyd 1982]. The quality of extracted contours are measured by their iso-contour error against the ground truth continuous growth field (refer to Figure 12c). Moreover, since the iso-contour error can be minimized with no contours detected, we additionally report the ratios of the ground truth contour length and count to confirm that a sufficient length and amount of contours have been detected, where ground truth contours are those extracted from the ground truth annual ring localization image (refer to Figure 12e). Our method outperforms alternatives, with the ablation showing a 75% higher median average iso-contour error and the best-performing baseline (1) exhibiting a 53% higher error (Figure 22). Moreover, the length and count ratios of the baselines deviate significantly from 1.0, indicating that extracted contours are either overly few and overly short, or overly long and overly many.

6.3 3D Procedural Growth Field Fitting

This section presents an ablation study focusing on the optimization of annual ring distortions (Section 6.3.1). An analogous analysis of the pith estimation step and growth rate (R) parameter resolution can be found in supplemental materials B.1 and B.2, respectively.

6.3.1 Optimization step 2: distortions. In global structure inference step 2, we optimize the distortions of the growth field, which are adjusted through the control radii ($R \in \mathbb{R}^{n_h \times n_a \times n_r}$), and the gray-map (M) from which the iso-values of the annual rings are extracted (refer to Section 5.2.3). Possible questions includes, is it important

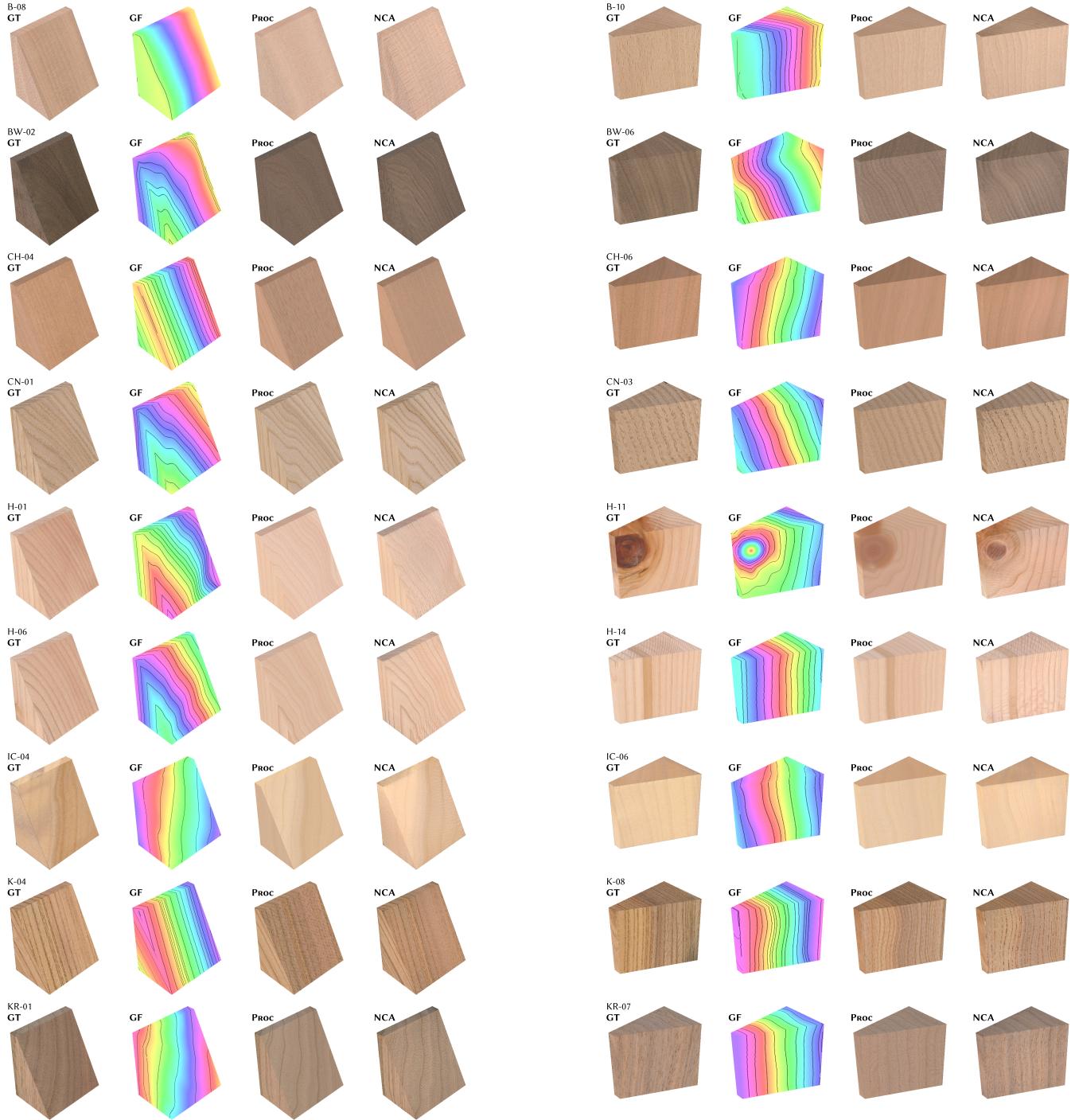


Fig. 17. Qualitative validation (continued on the next page). This matrix covers two samples (columns) from the test subset of each species (rows), showing a held-out ground truth photograph of the physically cut wood cube (sub-column 1), compared to slanted cuts through the reconstructed growth field (sub-column 2) and synthesized solid wood textures (sub-column 3, 4). When comparing the outputs, note that, while it is our objective to closely infer the annual ring locations relative to the reference, we do not expect to reconstruct texture details (pores, rays) with a one-to-one pixel correspondence. Rather, we effectively model their distributions. See Section 6.1 for further discussion of these results. Videos of rotating cubes for all 38 samples can be found in Supplement C.

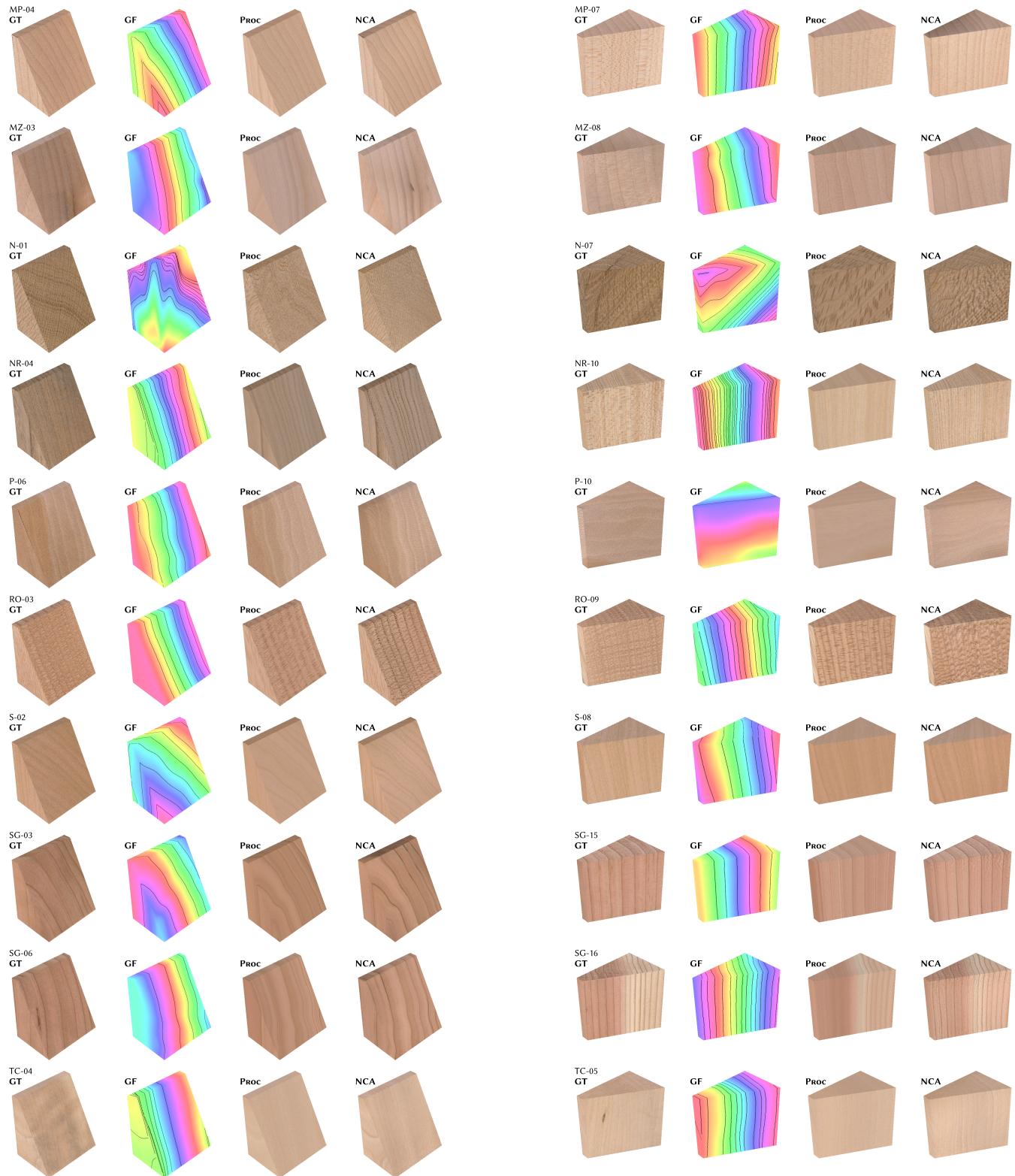


Fig. 18. Continuation of Figure 17.

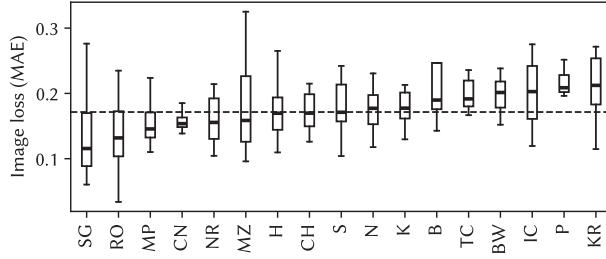


Fig. 19. Accuracy of annual ring localization image translation. Image loss of each species of U-Net generated annual ring localization images. The species are organized by ascending order of loss. The dashed line indicates the median image loss across all species.

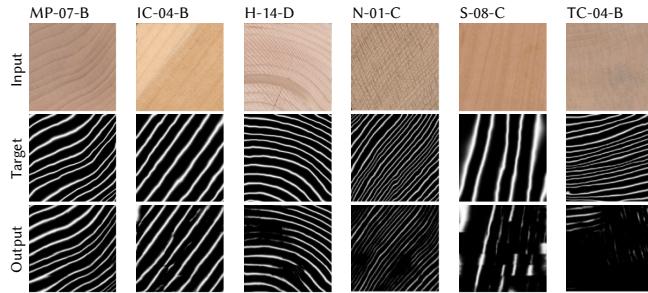


Fig. 20. Visual output from the annual ring localization image translation. Top: color image of the wood (input). Middle: ground truth annual ring localization images created from manual annotations (target). Bottom: U-Net generated annual ring localization images (output).

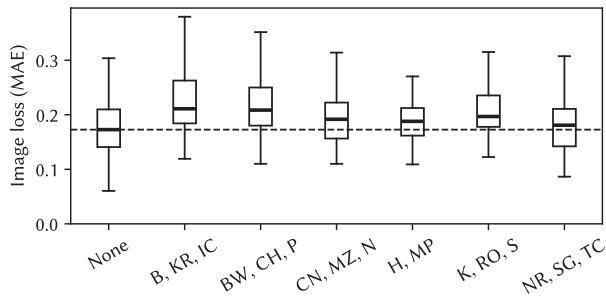


Fig. 21. Generalization test of annual ring localization image translation. Box 1 ("None") represents the results when the network is trained on 80% of all species and evaluated on the remaining 20%. Boxes 2–7 ("B, KR, IC," and so on) show the results when the network is trained on 100% of the samples of all species except a specific group of 2–3 species and evaluated on the unseen species in that group. The dashed line indicates the median loss of box 1.

that R represents the growth speed at a point rather than the explicit growth value, and the iso-contour loss necessary? We ran ablation experiments to answer these questions. Specifically, we compare our method to two ablations: 1) with an alternative explicit construction of R , 2) without iso-contour loss (just the image loss between target and output annual ring localization images drives

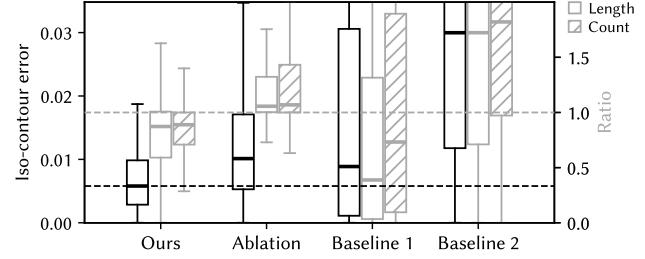


Fig. 22. Quality of extracted contours. Comparison between our method, an ablation, and two baselines. Each box shows the distribution of the average errors and ratios for the 228 images (6×38) in our test set. Lower iso-contour error indicates that the contours better follow the zero-gradient of the ground truth growth field. The dashed black line shows the median average iso-contour error of the proposed method (0.006). The dashed gray line indicates the ideal ratio (1.0) of contour lengths and counts.

the optimization). We evaluate the results against the ground truth annual ring annotations by two metrics. First, if the annual ring localization is correct, the color values of the annotated pixels should be white, and therefore, we report the average pixel colors at the annotation pixel locations. Second, we measure the iso-contour error of the ground truth annotated annual ring edges in the underlying growth-field from which the annual ring localization is constructed. This measures how well the annual ring pattern in the procedurally generated annual ring localization images follow the ground truth shapes.

Our method creates outputs with a lower median iso-contour errors, while median color values are similar for all methods (Figure 23). This is confirmed by the visual outputs, where we observe that estimated annual rings in the ablations frequently “jump” between different GT annual rings, that is, not following their shape although hitting many peaks (Figure 24). In ablation 1 (explicit construction of R) there are visual artifacts caused by this construction not inherently guaranteeing that an inner radius is smaller than an outer radius. This shows up as annual rings crossing each other, which is anatomically infeasible in wood growth where layers of annual material growth are subsequently added in the outward direction.

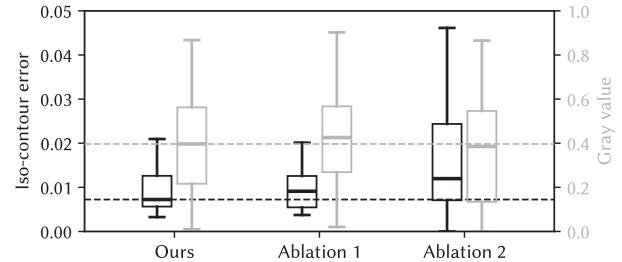


Fig. 23. Ablations of annual ring distortions and locations optimization. Each box shows the distribution of losses for the 38 samples in the test dataset. A better estimated annual ring localization image is characterized by a lower iso-contour error (ideally 0.0), and a higher gray value (ideally 1.0, white).

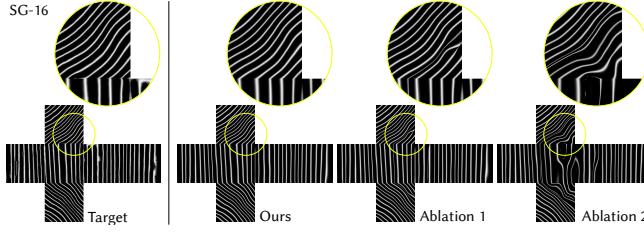


Fig. 24. Visual outputs from the ablation study of the annual ring distortions and location optimization. The optimization target are the external annual ring localization images generated by the U-Net (along with the contours extracted from it). In the ablations, annual rings tend to jump up or down between different GT annual rings.

6.4 Ablation of NCA

NCA generally excel at synthesizing repetitive patterns or textures without strong global structures. Pajouheshgar et al. [2023] showed that positional encodings can help capture some long-range correlations of the target texture. However, by ablating the wood-specific conditioning and omitting B and G from the NCA architecture, we showed that positional encoding alone is insufficient for producing coherent solid wood texture. Without our wood-specific priors, the annual rings become discontinuous (e.g., CN-01), the rays form in an incorrect direction (e.g., B-08), and the knots fail to form properly in the synthesized textures (e.g., H-11, Figure 25). This highlights that while positional encoding can help NCAs to model some aspects of a global structure, they cannot substitute our global wood structure priors.

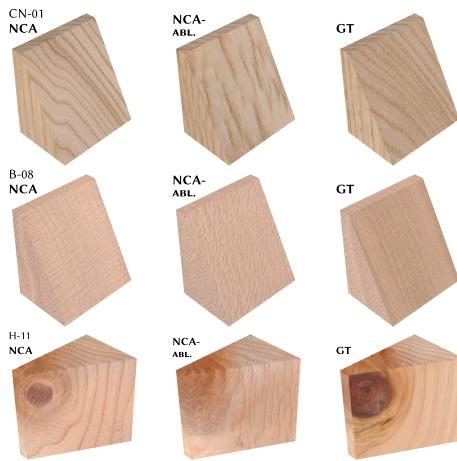


Fig. 25. NCA ablation comparison. Omitting the priors of the global wood structure leads to discontinuous annual rings (CN-01), incorrect orientation of rays (B-08), and indistinct knot structure (H-11).

7 LIMITATIONS

We have not yet captured samples in the *Mokume* dataset under varying lighting conditions, the dataset is limited to one sample size ($[4.0 \text{ cm}]^3$), and, although we included samples from many (17) species, this list is not exhaustive.

We approximate the pith as a straight line, and our parametrization of annual ring distortions is based on the assumptions that annual rings are star-shaped relative to the closest point the pith axis (or the knot axis). While a more complex formulation of the pith and distortions is unnecessary for our target samples, it could prove beneficial for handling highly distorted wood instances. While a more complex formulation of the pith and the distortions would be unlikely to yield better results for our target samples, it could prove beneficial for extremely distorted wood instances. Moreover, we model only alive knots (not dead or broken off ones), do not apply growth distortions to the knots, and approximate their central skeleton as a straight line.

As for texture synthesis, our procedural texturing model is a simplification of the state-of-the-art ([Liu et al. 2016] refer to Section 5.3.1). The main limitation of the NCA is that a single state tensor ($256 \times 256 \times 256 \times 12$) requires 384 MiB of storage in float16 precision. Backpropagating derivatives through a sequence of NCA updates requires intermediate states to be held in memory, which can saturate the memory of even the largest GPUs on the market.

8 CONCLUSION

The *Mokume* dataset provides a comprehensive new resource for wood structure modeling, offering exceptional diversity by covering various species with high-resolution multimodal data. We demonstrate how the combination of this dataset with computational models has powerful predictive capabilities, evidenced by high-fidelity synthetic wood textures that closely align with unseen ground truth data.

Central to our approach is the use of annual ring patterns as a deterministic feature, while fine-scale details (rays, pores, etc.) are treated as a learnable stochastic distribution. A compelling avenue for future research could involve extrapolating beyond the sample's boundaries. This would necessitate a modified methodology focused on capturing the overall "style" of distortions rather than achieving an exact match.

The potential applications of inverse procedural modeling are numerous and span diverse fields. Examples include predicting the visual outcome of sculptural pieces before physical carving, synthesizing extensive libraries of realistic materials for digital rendering, or the inference of non-visual properties: since the global structure of wood determines its mechanical properties, we envision the use of growth fields to augment simulations of material deformation and strength, using the resulting insights to guide irreversible processes such as milling and cutting.

Another potential research area is the directional reflectance behavior caused by the anisotropic nature of wood fibers. While previous research required complex goniophotometric measurements to infer their properties, we hypothesize that such effects could also be retrofitted to our work, as the fiber direction is inherently tied to the growth field.

Besides serving as a benchmark for procedural and learning-based texture synthesis, we hope that the release of the *Mokume* will catalyze interdisciplinary research to explore the manifold properties of wood.

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