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WHEN ACOUSTIC TOMOGRAPHY MEETS RESISTOGRAPH

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ABSTRACT

The paper presents an integrated approach to assessing the health and structural integrity of trees and wooden logs by combining acoustic tomography with resistograph measurements. Traditional methods are extended through the fusion of data from two complementary diagnostic tools. The first, an acoustic tomograph, detects internal decay and structural anomalies by measuring the propagation delay of elastic waves through wood. The second, a resistograph, assesses the mechanical properties of wood by recording the force required to drill into the material. A set of custom Python scripts has been developed to synchronize and merge data from both devices, enabling a more comprehensive and precise interpretation of internal wood conditions. This combined methodology offers improved diagnostic accuracy and has potential for application in forestry, arboriculture, and wood quality assessment.

Keywords: acoustic tomography, resistograph, wood quality assessment.

1. INTRODUCTION

Tree safety and mechanical stability are a crucial part of greenery management in cities. To ensure the structural stability of trees and reduce the risk of failure, several methods have been developed and implemented by cooperation between scientists, arborists, and wood researchers. The primary interest of these methods is to detect decay, cavities, cracks, ring shakes, and other types of wood damage (Soge *et al*., 2021) and (Proto *et al*., 2020). Note also that the methods developed for tree inspection can be used generally to evaluate the wooden logs or parts of wooden constructions.

A couple of scientific devices are available for both noninvasive and invasive tree or wood inspection. Especially acoustic tomography and microdrilling are well-known methods that are supported by commercial devices. However, a single method is usually not capable of giving full details of the status of the tree or the log. For this reason, it is suggested to combine more methods (Papandrea *et al*., 2022).

In order to make accurate predictions, it is necessary to understand the background of the methods and measuring devices.

For an acoustic tomograph, a set of sensors is attached to the tree, and the time of flight of the acoustic signal is measured between each pair of the sensors. This time of flight (TOF) and the distance between sensors are used to estimate the speed of sound wave propagation in the cross section. The sound speed is related to the mechanical properties of the material. This method usually gives a good estimate of the health status of the cross section even though it does not reflect the physical background of the wave propagation. Really, as a consequence of the Huygens and Fermat principles, the medium with higher speed of propagation is preferred by the sound ray, and thus the travel path of the sound is not a geometrically straight line. The real sound propagation path avoids material imperfections. However, this effect can be interpreted equivalently as a slowdown of direct rays on defects. Consequently, linear defects such as cracks or ring shakes near the center appear as central decay or a cavity on a tomogram (Rinn, 2015). Thus, the acoustic tomogram does not represent the local properties

of the wood but rather detects the parts of the cross section that are mechanically interconnected and therefore increase the mechanical stability of the whole structure (Rinn, 2015). It is also confirmed by experiments that cracks may in tomograms appear as big "fat" decayed zones even if only sound wood is present next to these cracks (Wang *et al.*, 2023). Another issue is that certain fungal species may influence the mechanical properties of the wood without affecting acoustic properties. Such behavior has been confirmed for *Kretschmeria deusta* (Cristini *et al.*, 2022) and (Schwarze *et al.*, 1995).

The microdrilling is typically performed by a resistograph device. A long, thin shaft is used to drill the hole into the material, and the drilling resistance is recorded as a function of the length of the drill hole. The sensitivity of the device even allows dendrochronological tree age estimation for certain species with wide tree rings (Szewczyk *et al*., 2018).

The combination of an acoustic tomograph and a resistograph offers an integrated approach that helps overcome the limitations of each individual method, enabling a more accurate assessment of the condition of the examined object, such as a tree or wooden log. This method was employed by (Rinn, 2015) to highlight that ring-shakes, which separate the central part of the tree from the outer wood, can be misinterpreted in tomographic images. Similarly, cracks may produce distortions of the same type (Wang *et al.*, 2023).

The output of the resistograph is typically in the form of a data chart with depth on a horizontal axis and drill resistance on the vertical axis. From the local decrease of the resistance, it is possible to judge the presence of a defect. However, the graphical representation in the depth-resistance coordinate system does not reflect the geometry of the cross section and makes it difficult to determine the defect location.

The aim of this work is to enable synchronized interpretation of the data from the acoustic tomograph and resistograph and provide a tool that allows merging data from both devices for better and more accurate interpretation. The basic idea will be to visualize both data in one unified geometry, which corresponds to the cross-section plane. A set of tools for creating such a visual representation has been developed in Python, which is nowadays a standard for scientific data processing.

2. METHODS

The wave propagations in standing trees and in stem sections with artificial cavities differ (Strobel *et al.*, 2018). In order to get the results as representative as possible, the data have been collected on standing trees that have been intended for felling. Six *Tillia cordata Mill* trees have been selected in Valdštejnova alej (Linden alley) in Jičín, Czech Republic (50.4465947N, 15.3724022E). These mature trees have been historically damaged by severe pruning (topping), with varying extents of internal defects in the trunk. Individuals were selected from the row adjacent to the road. Their habitat conditions in terms of stress load are therefore comparable. Dendrometric parameters differed significantly, especially in trunk diameter, with height varying around 8 m for all individuals.

The acoustic tomograph Fakopp ArborSonic 3D with 12 sensors has been used for the acoustic method. Each TOF has been established as the mean value of five measurements. The device RESISTOGRAPH® 4453 with 0.01 mm resolution has been used for microdrilling. Drilling was performed midway between each pair of adjacent sensors in a radial direction.

The data from the acoustic tomograph have been processed by the dedicated software ArborSonic 3D v 5.3.162 with a custom Python library (Mařík *et al*., 2024) based on EBSI and RSEN+SISE methods described in (Du *et al*., 2015) and (Du *et al*., 2018), respectively. Note that both approaches produce comparable outputs, and the only quotable difference was in the output format. In the first case the tomogram is obtained as a PNG file, and thus the coordinates in the image are in pixels and do not correspond to the coordinates associated with the cross-section and with sensor positions. In contrast, the second method utilizes the coordinates of the cross-section and produces the sound speed as a value rather than just as a color on a color scale. The second option has been used as a more comfortable one for data processing. However, the PNG option is also possible and has been used to merge the resistograph data with the cross-section photo (Mařík & Cristini, 2025).

The following algorithm has been used to convert data recorded by the resistograph to data visually represented by the colored bars in a 2D plane.

Input:

Node coordinates u_i, $i \in \{1,\ 2,\ \ldots,\ n\}$ centered at the origin, i.e. $\sum_{i=1}^{n} u_i = 0$.

Drilling resistance $f_i(t)$ on the path from the middle point of the segment $u_i u_{i+1}$ to the tree center as a function of drilling depth t .

An interval for t .

Output:

Colored bars in 2D plane. Each bar is at the position of drilling, and the color corresponds to the drilling resistance.

Notation:

Let $u_{n+1} = u_1$to simplify the notation and unify the formula for all indices.

Algorithm body:

Step 1. The middle point m_i of the segment $u_i u_{i+1}$ is $m_i = (u_i + u_{i+1})/2$.

Step 2. The unit vector e_i from the middle point to the center is $e_i = -m_i/|m_i|$, where $|m_i|$ is the Euclidean norm of the vector m_i. (Note that it is possible to treat the point m_i as a vector and thus a norm makes sense here.)

Step 3. The drilling resistance $f_i(t)$ belongs to the point $m_i + t \cdot e_i$. For all values of t under consideration, draw a corresponding mark to the 2D plane.

Step 4. Repeat from Step 1 to Step 3 for all values of i.

Algorithms have been realized in Python with common libraries for data and image processing, such as NumPy, Pandas, SciPy, and Matplotlib. For a practical implementation, the drilling resistances have been visualized as short line segments perpendicular to the drilling path with color corresponding to the resistance values. For convenience, a scale can be drawn along the drilling path. Red-black code has been used for this purpose.

The resistograph data are highly variable curves, and smoothing and downsampling are necessary for a reasonable visualization. The Savitzky-Golay filter has been used for data smoothing, since it preserves peaks of the data and allows fast and reliable signal processing. See also Figure 1.

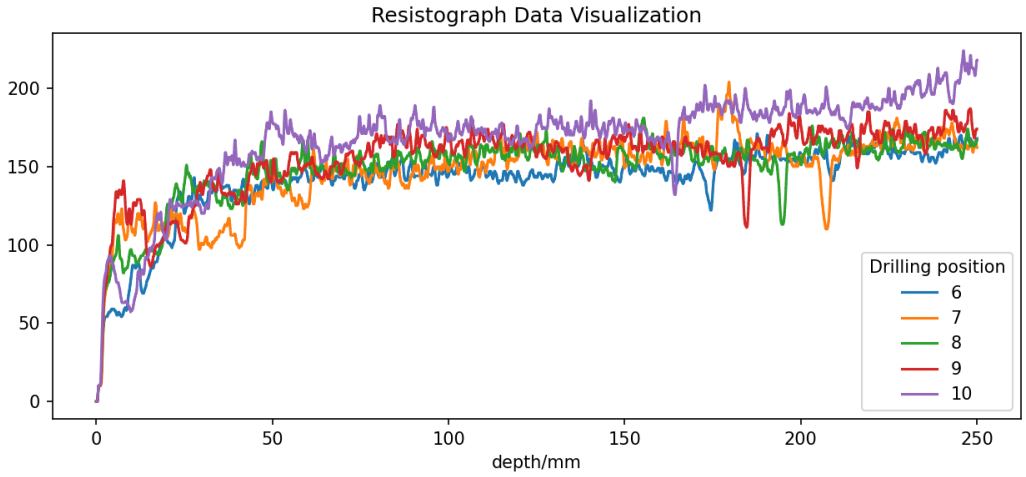


Figure 1. *The resistograph data along five drilling paths. Each of the curves has a short dropdown between 150 and 220 mm. This is an indication of damage at the corresponding position. The position is numbered according to the smaller sensor number. Drilling position 7 is between sensors 7 and 8.*

The trees have been felled, and the stem discs have been transported to the laboratory. Among others, the photographs of the discs have been used as a background image for the resistograph data to compare visually the correspondence of the drilling resistance with the stem condition.

3. RESULTS

The final code, which allows reading resistograph files, drawing the data in the stem cross-section plane, and optionally using a PNG image as a background, has been published on GitHub (Mařík & Cristini, 2025). The code is written in a modular way. It can be used to read the data in the native form saved by the resistograph, filter the data, and draw in the cross-section plane. The script may run from a command line or as a library.

An application of the scripts to tree number 5 is in Figure 2 on the left and shows the plane of the cross section with resistograph data visualized as colored bars. The columns (roughly) correspond to the drilling holes, and the colors correspond to the drilling resistance. Dark and white colors correspond to low and high drilling resistance, respectively. Consequently, a dark strip in the column indicates a short local decrease of the mechanical properties (could be a crack or ring shake), whereas the wide dark region would correspond to the cavity or degraded wood. Note also that the resistance typically increases from the boundary to the center, and thus we explore the local trend (local increase and decrease) rather than the global trend and actual resistance values.

The right part of Figure 2 shows a combined image with a tomogram and selected resistograph data. The columns with drilling resistance have clear black strips that reveal a decrease of mechanical properties. Despite the fact that the tomogram suggests a cavity in the center, the resistograph does not detect anything other than just a short local drilling resistance decrease. Thus, the defect in the stem is located along a narrow region and does not spread out in a large area.

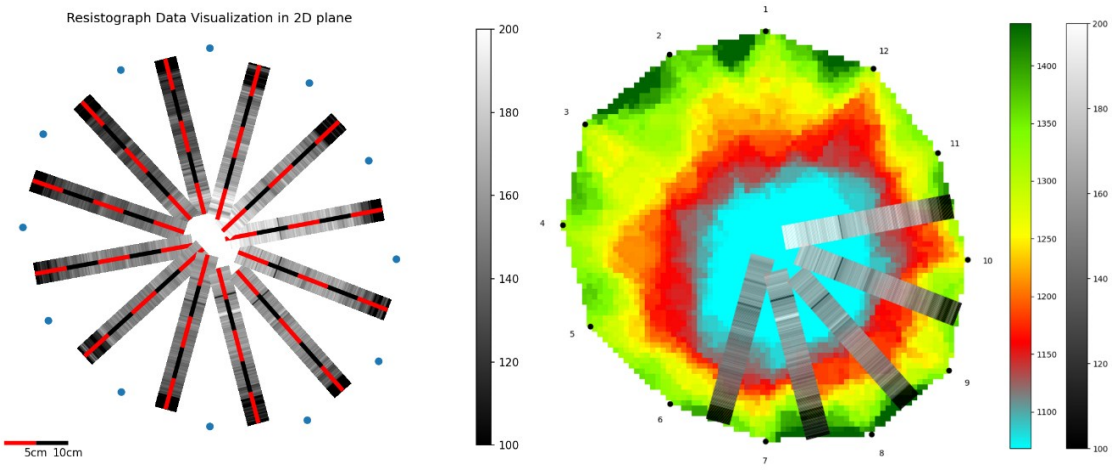


Figure 2. *Resistograph data projected to the 2D cross section of the stem on the left. The same data with a tomogram background on the right. Note that the tomogram suggests a central cavity, which contradicts the resistograph data showing just a narrow region with degraded mechanical properties (the black strips across selected bars near the end).*

4. DISCUSSION

It is well known that for any device used to evaluate trees of wooden logs, a skilled operator is required to interpret the results of the device correctly. Two or more methods are typically used to determine the health condition of the wood (Soge *et al.*, 2021). The toolkit presented in the paper simplifies the simultaneous combined interpretation of the tomographic and resistographic tests and makes the health status prediction more accurate.

Among others, the method allows distinguishing between central cavities-like damage shown on acoustic tomographs and linear damage such as cracks or ring shakes. This allows us to confirm or reject the presence of hidden central damage, which spreads out on the larger area of the tomogram but allows an alternative interpretation as a linear crack.

Note that coding the values of drilling resistance as colors along a line yields less precise information than the visualization using 2D curves in depth-resistance space. Thus, careful smoothing and downsampling are necessary. Since we are interested in the peaks (mostly peaks down

corresponding to thin cracks), a filter that preserves these peaks is required. The Savitzky-Gollay filter is a tool that has been used successfully in similar situations.

Even in the case of combined results from two methods, some skills and knowledge of the background are necessary for correct and precise interpretation of the results. As an example, note that the black strips corresponding to the ring shake (which has been confirmed by physical inspection after felling) are not all aligned together (see Figure 2). The dropdown of the resistance on the drilling path between sensors 7 and 8 is shifted with respect to its actual position. For an explanation, note the white strip on the same drilling path. This could indicate the presence of a knot, which slightly influenced the drilling direction. As a consequence, the position of the drilling path in the cross-section plane does not correspond completely with the actual position of drilling. For this reason, a general trend in the curves is in some sense more important than the exact position of the characteristic signs of the curve.

Because Python is a widely accepted data processing tool, many libraries are available for further data preprocessing or postprocessing. As one particular example, it is possible to blend two or more images in a Jupyter notebook using the tool (Octoframes, 2025). An example with mutual comparison of four images is shown in Figure 3. Other possible extensions include various GUI-like interfaces, which can be used to develop a user-friendly interface to the toolkit. Thanks to the modularity of the toolkit and the widespread use of the Python language, it is even possible to use LLM for certain programming tasks, the approach referred to as *vibe coding*.

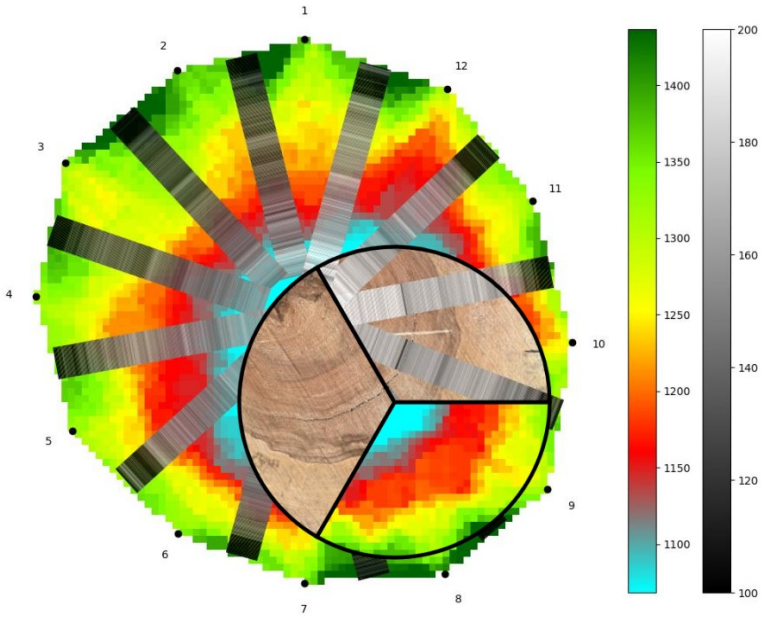


Figure 3. *An example of postprocessing. A swipe comparison of four images (a photo of the cross-section and tomogram, both with and without the resistograph data) which allows us to explore the output of measurement devices and compare with the actual state of the tree. The live version is available on https://arborist-mendelu.github.io/resistograph_meets_tomograph . The colored scale is the speed of the sound; the monochromatic scale is the drilling resistivity.*

CONCLUSIONS

It is well known that in order to get more precise predictions on the health status of trees or wooden logs, a combination of more methods is desired (*Soge et al*., 2021). A toolkit in the form of Python scripts has been created to simplify a simultaneous visualization of data from tomograph and resistograph. Visualization created by this toolkit allows merging data from two devices to a common geometry in the plane of the cross-section and allows distinguishing linear defects, such as cracks or ring shakes, from cavities or decay areas.

DATA AVAILABILITY

The Python code and the source data (node positions and resistograph data) are available on GitHub (Mařík & Cristini, 2025).

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