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Sapwood depth tool – proof of concept field prototype

Authors:

Nurzhan Nursultanov, Bill Heffernan

Research Provider:

University of Canterbury

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INTRODUCTION

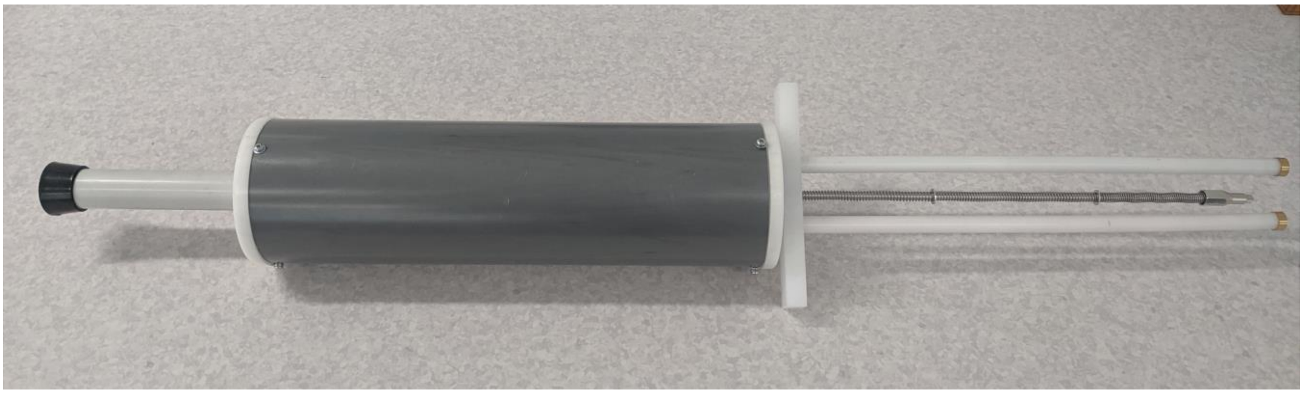
The sapwood depth (or size of heartwood) in standing trees can be measured by (1) the destructive method, (2) the semi-destructive method, or (3) the non-destructive method, with minimal damage to a tree. The destructive method involves cutting a tree and measuring the sapwood depth on the crosscut. This method relies on the colour difference between heartwood and sapwood or may require a special dye if the colour difference is not obvious. The semi-destructive method such as coring (Li, Apiolaza, & Altaner, 2018) or the sap flow velocity method (Pearsall, Williams, Castorani, Bleby, & McElrone, 2014) results in minor localized damage to a tree. Coring is fast but relies on the colour difference Relatively non-invasive methods such as Picus TreeTronic (Argus Electronic GmbH, Rostock, Germany) are complex, expensive, and have a long set-up time.

This report describes the concept of a new sapwood depth tool that determines the location of sapwood/heartwood interface by measuring the spatial electrical current change between two energized electrodes versus displacement below the bark surface and uses this to determine and record the heartwood depth with a specially developed android app. The report describes the main operational principles of the field prototype tool, including the updated algorithm of sapwood depth identification. The sapwood tool was tested on a rig that mimics the change of electrical resistance in a tree and on logs of *Eucalyptus globoidea* and *Eucalyptus nitens*.

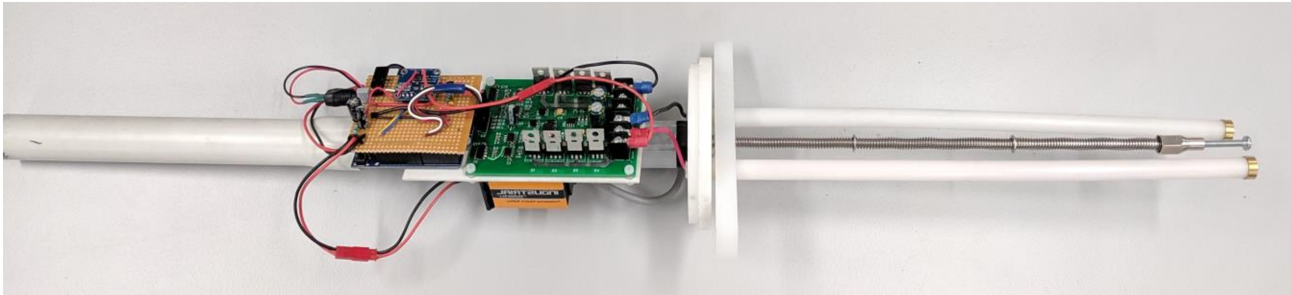
TOOL DESIGN

Hardware

Similar to the previous tool (Nursultanov & Heffernan, 2018), the field prototype tool has two probes. Inserted into two pre-drilled holes in a tree/log, the probes (**Figs. 1a & b**) have a square-wave alternating potential difference of 9V applied across them. Each probe has a 12mm overall diameter plastic tube (sleeve) with a brass tip connected to the square wave generator. This board converts the DC from the tool's internal battery into a 400Hz square wave AC voltage, using an H-bridge driven at 50% duty cycle. (DC excitation would cause electrolysis, while AC minimizes this effect.) A microcontroller board produces the H-bridge drive signal and digitizes values from an electrical current sensor, INA219, and a linear displacement sensor (LDS). The current and displacement values are measured every 100ms and are transferred to the android mobile phone app through Wi-Fi. **Figs. 1a & 1b** show the sapwood depth tool in and out of its outer case respectively, with a schematic diagram of the hardware design in **Fig. 1c**. The complete tool weighs 1.2kg and is 77cm long.



(a)



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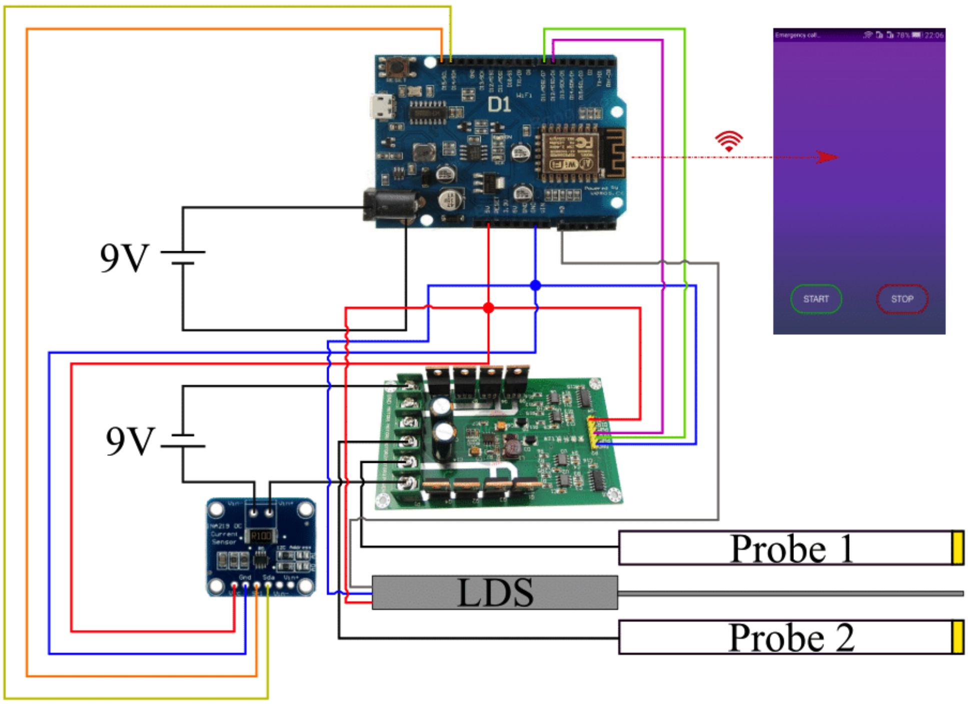


(c)

Fig. 1. (a) The complete sapwood depth tool; **(b)** the internals of the tool **(c)**; schematic diagram of hardware design.

Computational Algorithm

As the data is collected every 100ms, the raw data of electrical current and displacement has hundreds of values that contain noise – disturbance in the electrical signals - produced by hardware. Therefore, prior to the estimation of the current gradient as the tool depth changes, the raw data have to be filtered using a moving average algorithm, with a sliding window of five values. (In the previous study, the electrical current was measured every 1cm, and hence that data did not need to be filtered (Nursultanov & Heffernan, 2018).) The moving window shrinks near the endpoints to include existing elements. Thereafter, the filtered data is thinned to a 1mm spatial resolution to avoid unnecessary repetitions of data values, which could potentially lead to an error in the calculation of electrical current gradients. Finally, the thinned data was used to calculate the gradients (GD) using the following equation:

$$GD = \frac{I_j - I_{j+1}}{d_j - d_{j+1}}, \quad (1)$$

where I_j and I_{j+1} are the electric current measured at the depth d_j and d_{j+1}, respectively. In wood species with sapwood electrical conductivity higher than that in heartwood (e.g. *Pinus radiata, E. globoidea*) the lowest gradient (the highest magnitude negative gradient) value would appear on the interface, located between d_j and d_{j+1}.

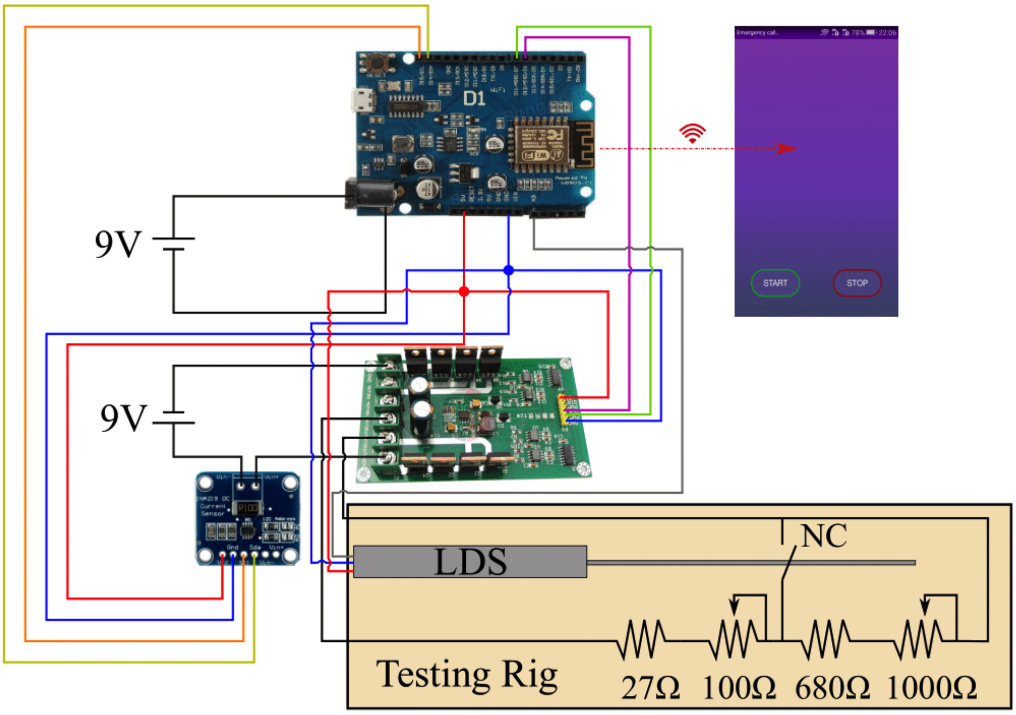
TESTING METHODS

Rig Testing

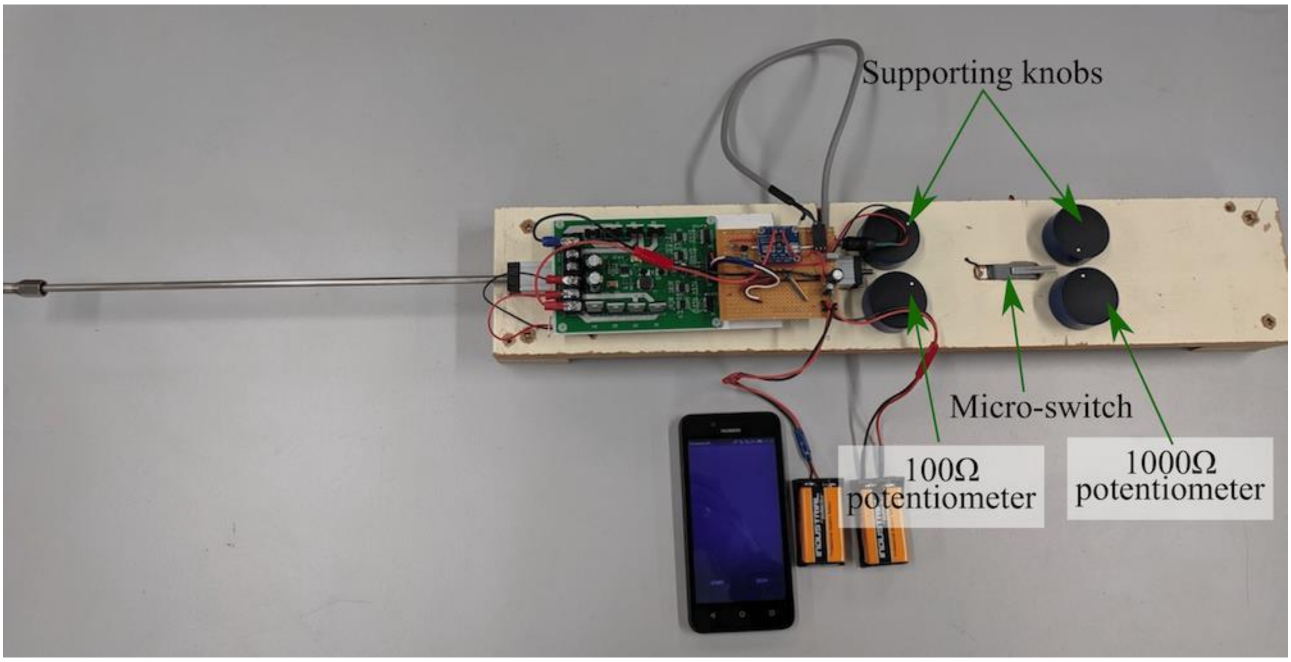
The sapwood tool was tested on a purpose-built rig that mimics the change of electrical resistance within a tree. The main advantage of this rig-based test method is the ability to perform a large number of trials within a laboratory environment, without requiring fresh wood samples for each trial.

Rig Design

The rig was made with two resistors of 27Ω and 680Ω and two rotating potentiometers of 100Ω and 1000Ω (**Fig. 2a**). The LDS with the mounted electronics was positioned on a rig with the LDS's shaft sliding between two sets of knobs (**Fig. 2b**). In each knob set, one knob rotated the potentiometer and the other supported the LDS's shaft alignment. In between the knob sets, there was a normally closed (NC) micro-switch, meaning that current would flow through the switch and not through the 680Ω resistor and the 1000Ω potentiometer. The shaft sliding between the first knob set pressed on the switch lever and opened the switch, forcing the electric current to flow through the more resistive path beyond this point, mimicking the change from sapwood to heartwood.



(a)



(b)

Fig. 2. (a) Schematic diagram and **(b)** photo of the testing rig. Note: The resistors shown in the schematic diagram are installed under the rig and hence are not visible in the photo.

Prior to testing the sapwood tool, the displacement of the shaft from the initial point was measured by a ruler. Following this the shaft was fully extended and the point at which the switch was activated was also measured. This procedure was repeated 10 times. Then, the sapwood tool was turned on and the shaft was slid along its full displacement (173 mm), changing the rig resistance and activating the switch. The android app recorded the raw data and determined the position of the switch (analogous to the sapwood/heartwood boundary). The experiment was repeated 10 times with the shaft being slid at different speeds.

Log Testing

Two logs, one each of *E. globoidea* and of *E. nitens*, were provided by the Forestry Department of University of Canterbury, Christchurch, New Zealand. Once arrived to the university premises, the logs were left in a freezer at -20ºC to reduce drying. Two days prior to the experiment the logs were defrosted at room temperature. The sapwood/heartwood interface was measured at three places in each log, the probe holes being drilled with a 12 or 12.5mm diameter twist bit located with a drill stencil. To improve the contact between the brass tips and the wood surface in the holes, a very small amount of a conductive gel* with 0.05S/m conductivity was added into the hole. The START button was pressed on the app and the probes were gradually inserted into the holes. When the probes were fully inserted, the STOP button was pressed and the sapwood depth was calculated. The obtained results were compared with the sapwood depth measured on a crosscut by a ruler.

*Note that such a gel can be produced at very low cost for field use.

RESULTS

Tool Verification

The displacement (measured by ruler) of the LDS's shaft from full extension to the point of switch activation was about 117mm (SD=±2mm, caused by the hysteresis of the switch). The same displacement measured by the sapwood tool was 116mm (SD=±3mm), where the deviation was due to the combined effect of the hysteresis and measurement error. **Fig. 3** shows a typical current drop and the switch's position determined by the sapwood tool in one of 10 trials.

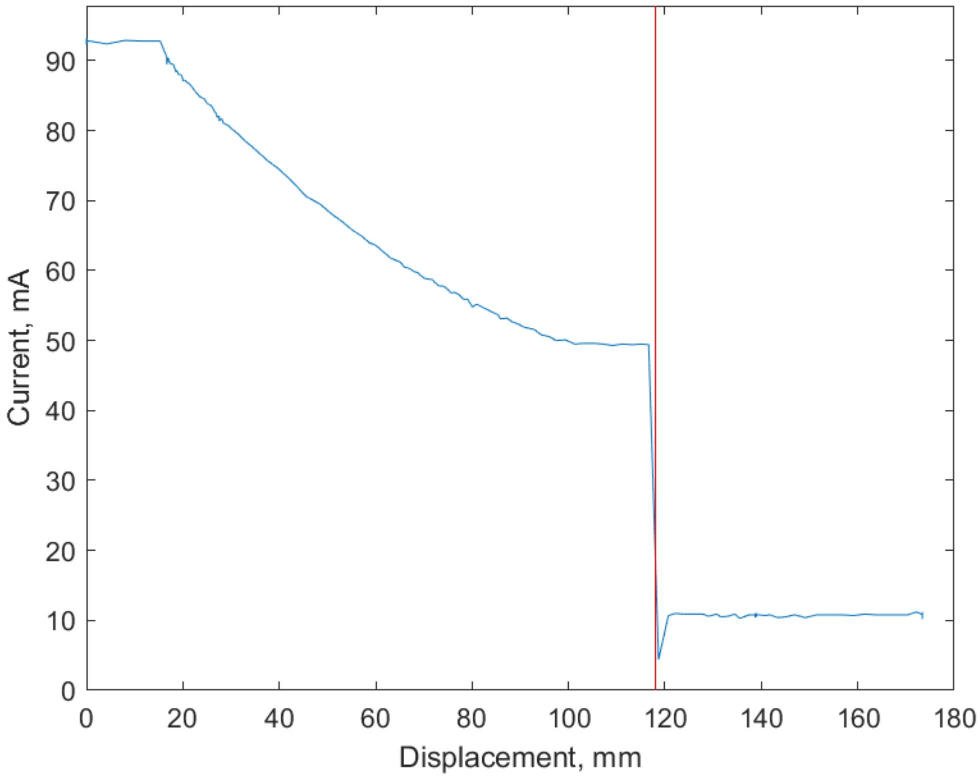


Fig. 3. Typical electrical current drop (blue) and switch position determined by the sapwood tool (red) in the tool verification test.

SW/HW interface validation

Fig. 4 shows the test logs selected for tool validation, with the drill stencil deployed in **Fig. 5**.

Fig. 4. *E. nitens* (left) and *E. globoidea* (right) test logs.

Fig 5. Drill stencil in position

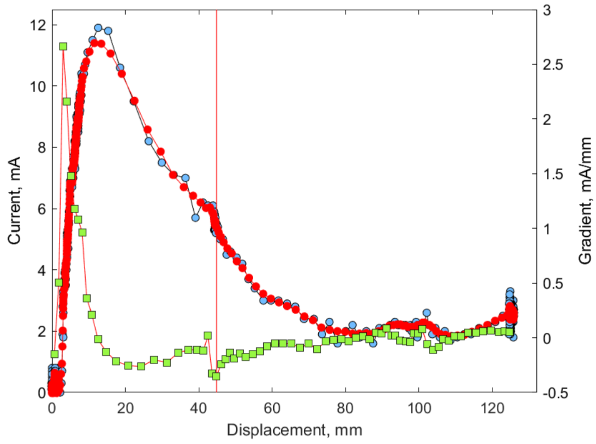
E. nitens

Fig. 6 shows the change of electrical current determined by the sapwood depth tool at three test locations within the *E. nitens* log. Similar to our earlier results (Nursultanov & Heffernan, 2018), electrical current increased initially and then gradually decreased, levelling off closer to the log centre. The initial increase of electrical current can be linked to two effects: (1) the existence of an external dry annulus in the log (Nursultanov & Heffernan, 2018) and (2) an increase of the contact area between the brass tips and the wood. First, although the log had been stored in a freezer, log drying was not fully supressed. Therefore, the external sapwood annulus was potentially drier and hence less conductive than the internal sapwood annulus. To verify this hypothesis, the sapwood tool should be tested on standing trees. Second, as the brass tips are 5mm long, the contact area increased with the insertion of the tips in to the holes. When fully inserted, the tips had the maximum contact area, assuming all air pockets at the contact surface were filled with the conductive gel. The higher the contact area, the higher the electrical current. However, this relationship can be non-linear, as current flow in wood is obscure due to wood's anisotropic and heterogenic structure. Employing computational modelling such as Finite Element Analysis (FEA) would allow us to quantify the effect of contact area on the electrical current measurement, consequently improving the algorithm and the accuracy of the sapwood depth tool. As *E. nitens'* heartwood is less conductive than the sapwood, the consequent decrease of electric current was caused by heartwood. Overall, the sapwood depth measured at Positions 1-3 showed an acceptable agreement with the depth values measured by a ruler (**Tab. 1)**.

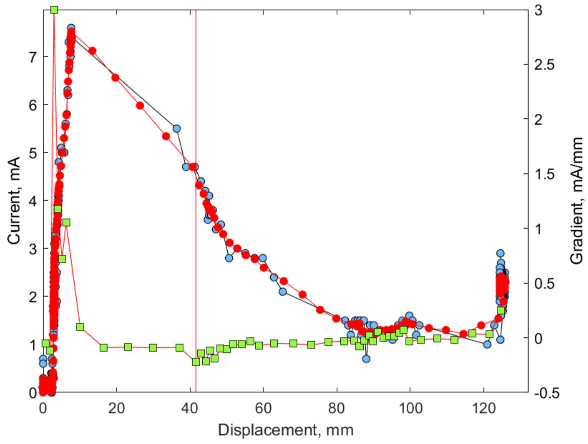
In addition, the data resolution at some parts of the measurement is insufficient (Fig. 6b). This can potentially lead to an error in the gradient calculation and to inaccurate estimation of the SW/HW interface. To increase the data resolution, the data ideally needs to be collected at a higher rate (e.g. 10ms between samples), and/or the speed of the probe movement in the holes must not increase beyond some predefined maximum. The latter can be achieved by adding a mechanical damper, to ensure a constant rate of probe insertion.

Tab. 1. Sapwood depth of *E. nitens*

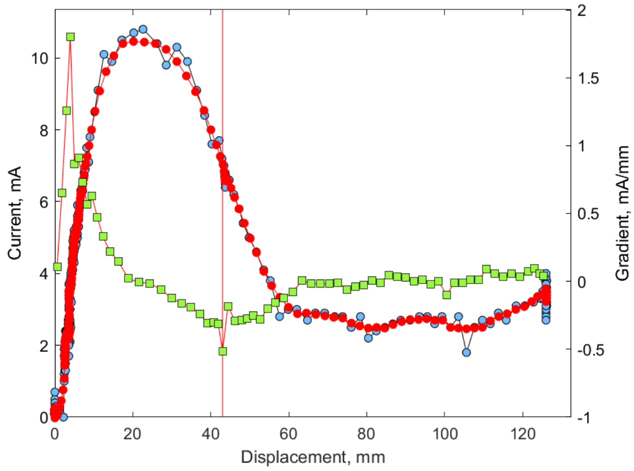
Positions	Ruler, mm	Sapwood Tool, mm
Position 1	43.5	44.8
Position 2	36.5	41.6
Position 3	42.5	43.0



(a) Position 1



(b) Position 2



(c) Position 3

Fig. 6. Change of electrical current with displacement within the *E. nitens* log at Positions 1-3. The blue and red circles denote the experimental raw and filtered data respectively. The green squares represent the gradient of electrical current calculated from the filtered data. The vertical red line indicates the SW/HW interface position estimated by the sapwood depth tool.

E. globoidea

Fig. 7 shows the change of electrical current in the *E. globoidea* log at three test locations (Positions 1-3). The curves show a similar pattern observed in **Fig. 6**. However, after about 10mm displacement, the current curve changes the slope at several points: (1) at about 20mm, (2) at 35-40 mm, and, in **Fig 7a**, (3) at about 60mm. Each slope change indicates a change in wood electrical conductivity and hence a transition between two wood types. However, as the existing algorithm looks only for a single change of slope, the sapwood tool picked only the change that was the most obvious in that particular trial. Once the log was sawn, the crosscuts showed that there was at least one additional zone, transitional wood (TW) that lay between sapwood and heartwood (**Fig. 8**). Furthermore, **Fig. 8** shows that there is another zone within the heartwood; in other words, the log's heartwood had two wood zones: the darker external annulus and the paler internal part. The transition between these zones occurred at about 60mm displacement, as shown in raw data recorded at Position 1 (**Fig. 7a**). The sapwood tool, using the existing algorithm, picked the SW/TW interface at Position 2 and the TW/HW interface at Positions 1 and 3 (**Tab. 2**). To identify all existing interfaces in wood species such as *E. globoidea* with SW, TW, and HW, the algorithm needs to be further improved.

Tab. 2. The sapwood depth of E. globoidea

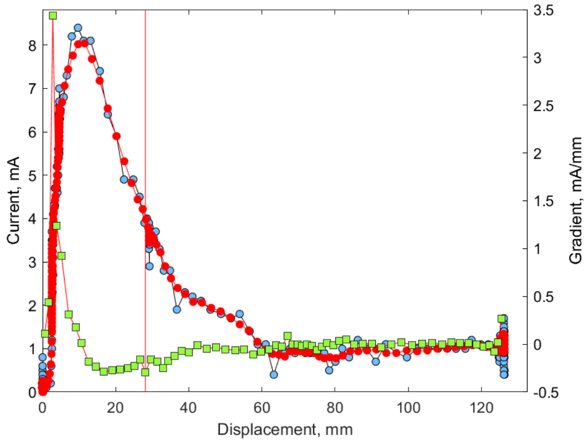
Positions	Ruler, mm		Algorithm, mm
	SW to TW	TW to HW	
Position 1	20.0	27.5	28.1
Position 2	20.0	28.0	20.9
Position 3	21.5	28.5	31.8

CONCLUSIONS AND FUTURE WORK

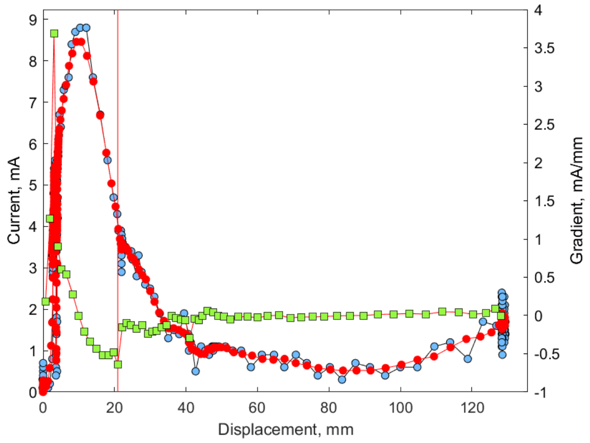
The sapwood tool shows an acceptable accuracy in the determination of the SW/HW interface in the *E. nitens* log with a single SW/HW interface. However, in *E. globoidea*, the sapwood tool identifies either the SW/TW or TW/HW interface (but not both), which was due to the limitation of the algorithm. Nonetheless, the raw data shows the change of electrical current indicating multiple wood zones. Hence, with suitable algorithm modifications, the tool could probably find the bark-cambium interface as well as sapwood/heartwood and, if applicable sapwood/transition and transition/heartwood interfaces. This could be of some importance especially on trees with thick bark, where standard mensuration techniques, e.g. using DBH tapes, may significantly overestimate the volume of standing timber, unless bark thickness is considered. The following improvements are suggested for building a commercial prototype:

- increasing data resolution to 10ms,
- installing a mechanical damper on the tool to ensure a consistent insertion rate,

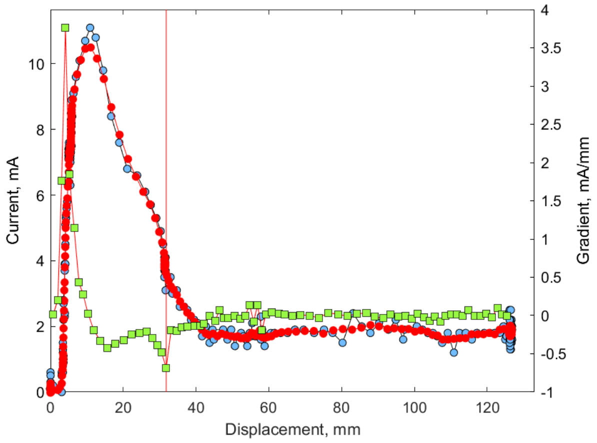
- modelling current flow caused by probe to study the effect of contact area on the electrical current measurement,
- testing the sapwood tool and algorithm/s on standing trees.



(a) Position 1



(b) Position 2



(c) Position 3

Fig. 7. Change of electrical current with displacement within the *E. globoidea* log at Positions 1-3. The blue and red circles denote the experimental raw and filtered data respectively. The green squares represent the gradient of electrical current calculated from the filtered data. The vertical red line indicates the SW/HW interface position estimated by the sapwood depth tool's existing algorithm.

Fig. 8. Two typical cross-cut views of *E. globoidea* with the distinguishable sapwood, transitional, and heartwood zones.

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