

TOWARDS A NEW TECHNO-AESTHETIC PARADIGM: EXPERIMENTS WITH PATTERN, TEXTURE AND COLOUR IN 3D-PRINTED WOOD-PLASTIC COMPOSITES

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Abstract

3D printing of wood-plastic composites (WPC) has the potential to create its own aesthetic paradigm by taking advantage of the possibilities of digital fabrication. This study explores the process parameters affecting the aesthetic of the resultant 3D printed product using the commercial wood-plastic composite filament LAYWOO-D3, and printed using a Leapfrog™ Creatr 1.75mm fused deposition modelling (FDM) system. The parameters explored were the temperature of the printer nozzle of the 3D printer, the velocity of the printer head and the toolpath of the extruder. These variables were manipulated with algorithms to incorporate key aesthetic attributes of wood such as the grain pattern, surface texture and colour. Study of these parameters will allow further insight into the creation of 3D printed wood-plastic composites and has the potential to forge a positive public perception of composites as a technologically advanced product that offers a functional and aesthetic alternative to natural wood.

Keywords: wood-plastic composite, fused deposition modelling, aesthetic, Perlin noise

Introduction

Natural wood products have an organic aesthetic that builds on properties such as surface finish, texture and colour. They offer sensory qualities that are ideally suited for further exploration in architectural designs. However, the architectural design potential of structural wood products is limited by traditional subtractive manufacturing methods and the inherent material properties and flaws of wood. Wood laminates have been used as a method of providing a wood aesthetic on the surface of composite products such as LVL (laminated veneer lumber) and can be applied to large scale façades (Suare et al., 2010). However, laminates can be difficult to use in structures with intricate details, as unsightly seams can be produced from the splicing of laminate at the edges (Kline, 2002). There are also issues with delamination and weathering in exposed situations (Kolb, 2008). The division between an internal and external materiality is governed by a double rationale designed to maximise functional and aesthetic performance of a product (Böhme, 2016). Homogeneity, both structural and aesthetic, is a key driver of this development that allows for the elimination of natural flaws (knots, for example) and an increase in economic viability.

Wood-plastic composites (WPC) has been more heavily used in structural applications since its inception, with current uses involving macro-extruded timber decking and railing (Klesov, 2007). Fabrication of WPC typically involves mixing of wood flour, plastic pellets and additives through a screw extruder that will melt and mix the compound. Wood flour can be sourced from wood product manufacturers directly, or obtained in the form of saw dust and shavings which is then milled and screeded to obtain wood flour. Additives added can include coupling agents, lubricants, fire retardants and UV stabilisers (Gardner and Murdock, 2010).

However, WPC has not seen widespread use on large scale structures or wider usage through additive manufacturing techniques. Through the use of computer aided design to perform the assembly of the structure in a digital model rather than construction on site, there is potential to take advantage of the composite's strength, ease of manufacture and aesthetic appeal by combining additive manufacturing with WPC for structural façade applications (Strauß, 2013).

Combining fused deposition modelling (FDM) with WPCs paves the way to realise the possibilities of creating large scale complex 3D printed structures. Research into the field of additive manufacturing with WPC have focused on the material composition of the filament to improve stiffness, tensile strength and compressive strength, and to optimise internal structure to gain compressive, tensile or bending capacity, as well as on the process controls to develop a consistent 3D printed object (Clark, 2014). However, there has been very little relevant literature that focuses on the aesthetic and the appeal to the end user. Furthermore, there has been little consideration in recreating the natural aesthetic of wood through the FDM process. The aesthetic of products generated from wood plastic composites using 3D printing has generally been homogenous, since the colour of the resultant print replicates the colour of the filament that is used in the 3D printer. Compared to wood laminate products, 3D printed wood composites overcome the division between an internal and external materiality. The composition of the printing material and the printing process create a plastic aesthetic whereby the surface of the printed element articulates the variables of the printing process whilst maintaining an identical material composition. Increasingly smaller components in timber composites result in more homogeneous material properties that are easier to manipulate and are substantially more consistent in comparison to natural wood. In 3D printed timber composites, structure is not necessarily expressed as structural core or grid on one side, and a surface or veneer on the other, but as areas of material that can be reinforced according to load paths (Lynn, 2011).

The aim of the study is to recreate visual appearance and texture of natural wood by developing process control mechanisms involving modifications to the material throughout the FDM process and the manipulation of the printing algorithms. The creation of a wood aesthetic on 3D printed WPCs has the potential to increase the marketability and economic viability of the final product, and increase the appeal of these products for both engineering and architectural uses.

Analysis of Natural Wood Grain

Techniques to measure the appearance of grains on wood were used in order to understand the parameters of natural wood that need to be replicated using the 3D printing process. These involved the measurement of the variance in the wood grain distribution across the grain and along the grain, and the distribution of the light and dark regions as shown in Figure 1. A sample of pine timber plantation wood was used to determine these properties at five locations along the specimen. The grain width was measured on a linear scale, while the ratio of light to dark regions was analysed using Adobe Photoshop® software by normalising the timber sample to highlight the contrast between light and dark as shown in Figure 2.

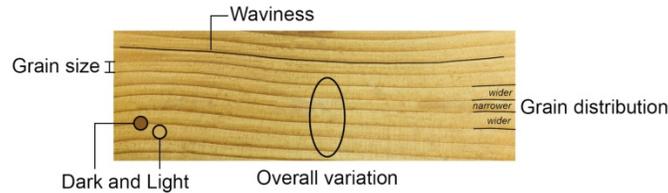


Figure 1: Parameters of natural wood which were measured



Figure 2: Left – colour image of pine timber sample; Right – normalised image with perceived dark regions made black and perceived light regions made white

The average grain size in the pine timber was measured to be 4.2mm. Measurement of the variance in grain size in the analysis of this particular pine timber sample revealed that there was a 27% deviation in direction 1, and an 8.3% deviation in direction 2. As shown in Figure 3, there is more variation in the thickness of the grains over the different layers (direction 1) than in the same layer (direction 2).

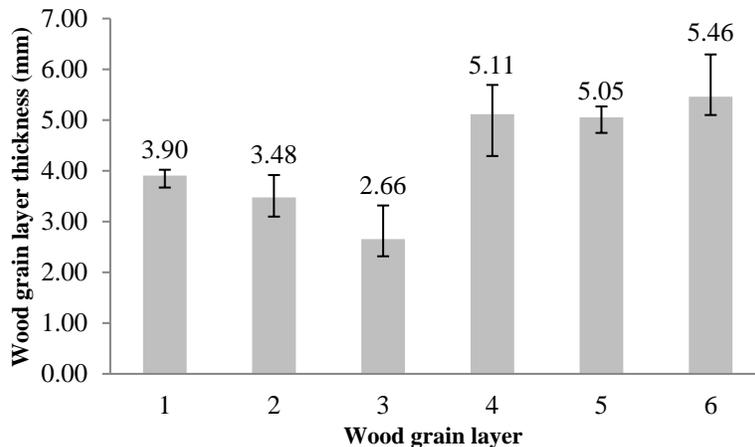


Figure 3: Average thickness of wood grain layers in the pine timber sample

Analysis of the colour intensity in the histogram (Figure 4) shows the range of brightness values on the wood sample, on a scale of 0–255, with 0 being absolute black, and 255 being absolute white.



Figure 4: Histogram of brightness of the pine timber sample

Perceived dark regions on the timber sample had an average absolute value of 185, while perceived light regions had an average absolute value of 220. The grey region is perceived to be within the values of 185 and 220. Through calculating the tributary areas on the histogram by using the area function in Rhinoceros® software, it was found that dark regions represented 10% of the sample, light regions occupied 65%, while the remaining 25% were considered to be grey. The proportional representation of light and dark regions also informed initial experiments on achieving the aesthetic of wood.

Variations in WPC Filament

Investigations into the use of LAYWOO-D3 WPC filament during the printing process explored the possible variations in tone of the resultant 3D print. Cube samples printed (Figure 5) using the LAYWOO-D3 WPC filament at a temperature range of 180–230°C were scanned and analysed using Adobe Photoshop® software. This revealed an absolute brightness difference of 10.2%. In comparison, the pine wood sample had a difference of 13.7% between the dark and light grains.

Printing the LAYWOO-D3 WPC filament at a higher temperature of 250°C caused shrinking in the vertical direction and spreading in the horizontal direction. This can be attributed to the lower viscosity of the WPC filament at higher temperatures compared to the temperature range of 180–230°C. Conversely, attempting to print at a nozzle temperature below 180°C induces a higher probability of the filament getting stuck in the extruder, as the temperature is not high enough to melt the filament in order to extrude it. In another study of 3D printing with LAYWOO-D3 WPC filament, Jovanovic (2015) also recommends a similar operating temperature range to create light and dark shades on the printed object.

The movement rate of the printer head also has an impact on the resultant tone of the samples. By default, the Simplify 3D software that converts the digital 3D model to the G-code required to print the object using the Leapfrog printer is programmed to feed the filament at a rate of 900mm/min when printing the exterior shell of a 3D object, which is linked to the

movement rate of the printer head. Printing at higher movement rate reduces the colour intensity of the print as the filament is exposed to high temperatures in the nozzle for a shorter period of time. However there is a limitation to how much the movement rate can be changed, as a higher speed can lead to delamination occurring between adjacent print paths, while a slower speed can lead to oozing of the filament and produce a line that is too thick.



Figure 5: Cubes with different tones printed at differing temperatures with LAYWOO-D3 filament

Manipulation of Printer Algorithms

3D printing that involves printing of the object using WPC filament without any further manipulation in the algorithm appears monochromatic. However, the combination of the analysis of the natural wood grain and the capabilities of WPC in the 3D printer can be linked to create an aesthetic that is visually reminiscent of natural wood. This techno-aesthetic can be produced through the integration of printer algorithms generated using Processing software, which is exported as a G-code file for the 3D printer to print.

The sequence of iterations performed to convert a monotonic print to a finished surface that bears resemblance to wood is summarised in Figure 6.

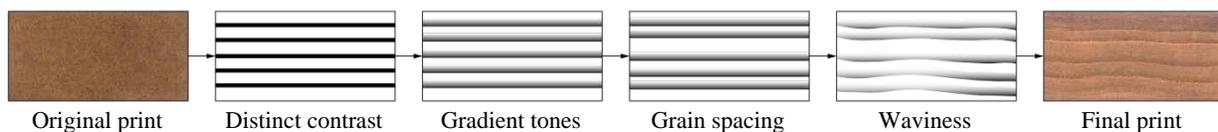


Figure 6: Process in converting the original monotonic print to achieve the final wood texture

Distinct contrast

Creating a distinct contrast between light and dark regions was achieved by employing two techniques, change in temperature and change in printer head movement. Figure 5 shows the different colour tones that can be produced by changing the temperature at the nozzle when the LAYWOO-D3 filament is extruded. Since printing at 250°C reduced the viscosity of the extruded filament and the resulting tone was similar with the 230°C print, the darker tone limit was set at 230°C.

Changes in the print head movement were incorporated into the feed rate value, which is explicitly expressed within the G-code instructions that is sent to the FDM machine to produce the prints. In the G-code, the value is preceded with the letter 'F' and is expressed in millimetres

per minute. The velocity of the print head on the Leapfrog Creatr FDM machine was varied between 450mm/min and 4800mm/min.

Gradient tones

Gradients across the grain were achieved primarily through the gradual variation in temperature as the printer head moves across the surface. This is achieved by instructing the printer to change to a certain temperature and continue printing. While the changes in temperature at certain part of the print are explicitly expressed instructions within the parameters of the 3D print, the nature of the 3D printer operation means it takes time for the nozzle to heat up or cool down to achieve that temperature. This presents an opportunity to create a gradient that is reminiscent of natural wood grain. As shown in Figure 7, the dark regions are printed at 230°C. While the majority of the print is set to 180°C as explicitly written in the G-code instructions, the natural air cooling of the nozzle means it takes time for it to reach that temperature, which produces the gradient between the light and dark regions.



Figure 7: Wood print with gradient tones from temperature change

Unfortunately creating gradient tones was less successful for different print speeds as slower print speeds, such as the 450mm/min feed rate in Figure 8, tend to create thicker print lines as the printer head tends to spread the filament over a greater area when it travels more slowly, eliminating the gradient effect across the grain. Faster print speeds, such as the 4800mm/min in Figure 8, has the tendency to break up along the tool path as there may not be enough filament being extruded to keep up with the high movement speed. Also changes to the print speed are performed in discrete steps, which reduce the opportunity for creating a gradient effect that would otherwise be achieved with a continuous temperature change.

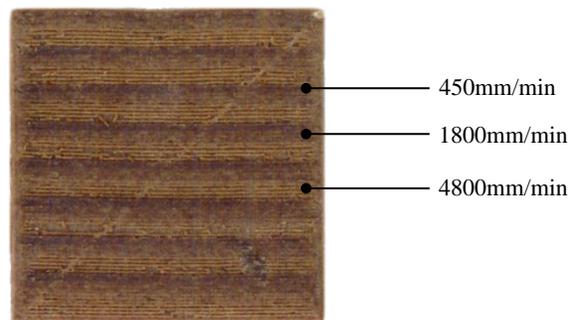


Figure 8: Wood print produced by varying print speeds

Grain spacing deviation

To develop the deviation across the grain, Perlin noise is used to add a random element to create the aesthetic of natural wood grain. Perlin noise is defined by pseudorandom numbers which have a smooth transition between neighbouring values. This has the effect of producing a more organic appearance for texturing purposes (Shiffman, 2012). On the other hand, pure noise would have a random variation with all values, which appears to be jittery, as shown in Figure 9.

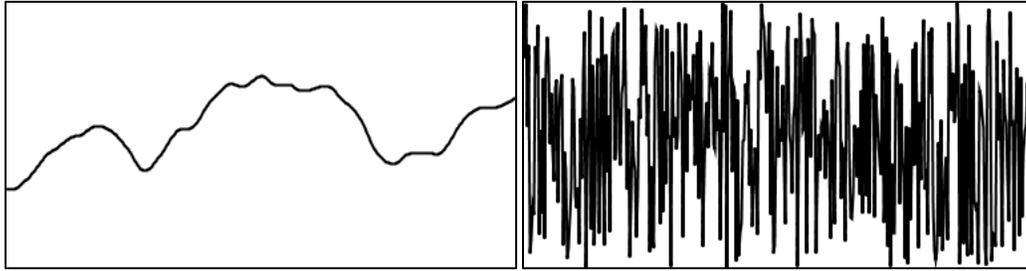


Figure 9: Left – Perlin noise is produced such that there is a smooth transition between neighbouring values; Right – Pure noise contains values which have no correlation with each other, resulting in a disordered output (adapted from Shiffman, 2012)

The grain width is determined by equation (1):

$$\text{Width} = \text{Average width} + k * (\text{noise}(n) - 0.5) \quad (1)$$

The value of k corresponds to the required deviation about the average width, while $\text{noise}(n)$ uses the Perlin noise algorithm that generates a pseudorandom value between 0 and 1. Since Perlin noise produces values with a smoother transition between different values, it has the effect of reducing the occurrence of spontaneous differences in grain width which may result in the generated grain width being close to zero or absurdly large. If Perlin noise is depicted visually as a monochromatic image, lower numbers would appear darker and high numbers appear lighter. As shown in Figure 10, the algorithm to vary the grain width, as represented in equation (1), can be depicted visually with darker regions or lower numbers producing closer spaced grains and lighter regions or higher numbers producing wider spaced grains.

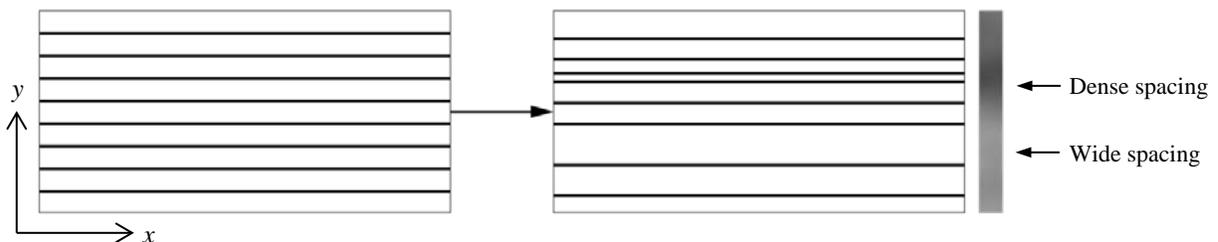


Figure 10: Application of a 1D Perlin noise map to create deviation of grain width

When translated to a print path in the FDM process, the start of the grain would be printed in the x-direction with the nozzle temperature set at 230°C and cool down to 180°C over time as the print progresses in the y-direction, before reheating to 230°C again when the new grain is printed.

Waviness along the grain

The Perlin noise algorithm can be expanded to 2D and can be visualised as a monochromatic pseudorandom map. By mapping the wood grain with the Perlin noise, the grain would either shift up or shift down depending on the value at a particular location on the map. This can be represented by equation (2):

$$f(x,y) = g(x,y) + c*(noise(x,y) - 0.5) \quad (2)$$

The function $g(x,y)$ represents the series of grains after the transformation of grain widths (Figure 10), which is used as a basis for further transformation to create waviness in the grains (Figure 11). The value of c corresponds to the required deviation about the original function $g(x,y)$ and can be varied to create a little bit of waviness or a lot of waviness. Two parameters are applied in $noise(x,y)$, which utilises the Perlin noise algorithm to produce a pseudorandom value between 0 and 1. The resulting function $f(x,y)$ produces a pattern that is dependent on the position in both the x and y directions. The waviness of the grain is translated in the actual print through the movement of the tool path. The print head moves gradually in the y -direction to create the waviness while it is predominantly moving side to side in the x -direction. The application of Perlin noise and its smooth transition between neighbouring values ensures that adjacent wood grain layers only deviate slightly from the previous layers, ensuring a consistent texture that is reminiscent of wood, as depicted in the diagram in Figure 11.

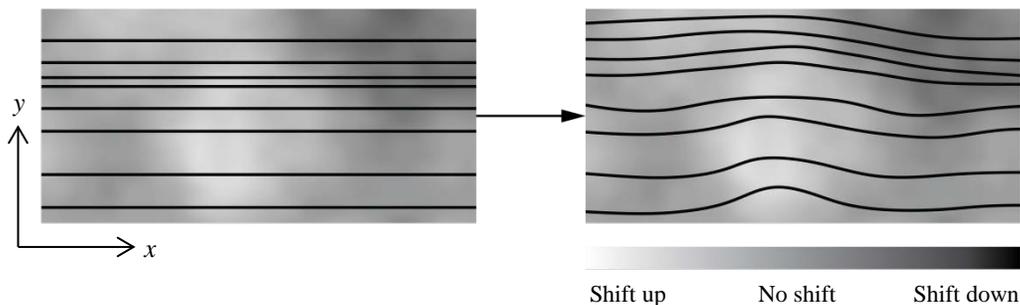


Figure 11: Application of a 2D Perlin noise map to create grain waviness

Manufacture of Techno-Aesthetic

Generation of the resultant print samples involved the printing of the base structural layers, followed by the pattern layer at the top. The pattern layer combines most or all of the combinations of printer algorithm manipulations. Due to the pseudorandom nature of Perlin noise, the generated G-code from the Processing software creates a different wood texture every time the script is run, resulting in a unique aesthetic every time.

All the wood prints were printed using 1.75mm LAYWOO-D3 filament between the temperature ranges of 180–230°C. A 0.35mm nozzle was attached to the Leapfrog Creatr printer head. The velocity of the print head was 4800mm/min for the three base layers and 900mm/min for the top pattern layer. The top pattern layer is the only layer where the actual aesthetic of the print is produced. Each sample piece has dimensions of 80mm x 40mm (Figure 12).

Variables which were changed to create different prints, either explicitly through the change in the Processing script or due to the pseudorandom variation in the G-code output, include the average spacing between grains, and deviation of the grain width. For the prints shown in Figure 12, the variables in the Processing script that were kept constant were the spacing between adjacent tool paths, which was set at 0.3mm, and the waviness deviation parameter, *c*, which is set to a value of 25.

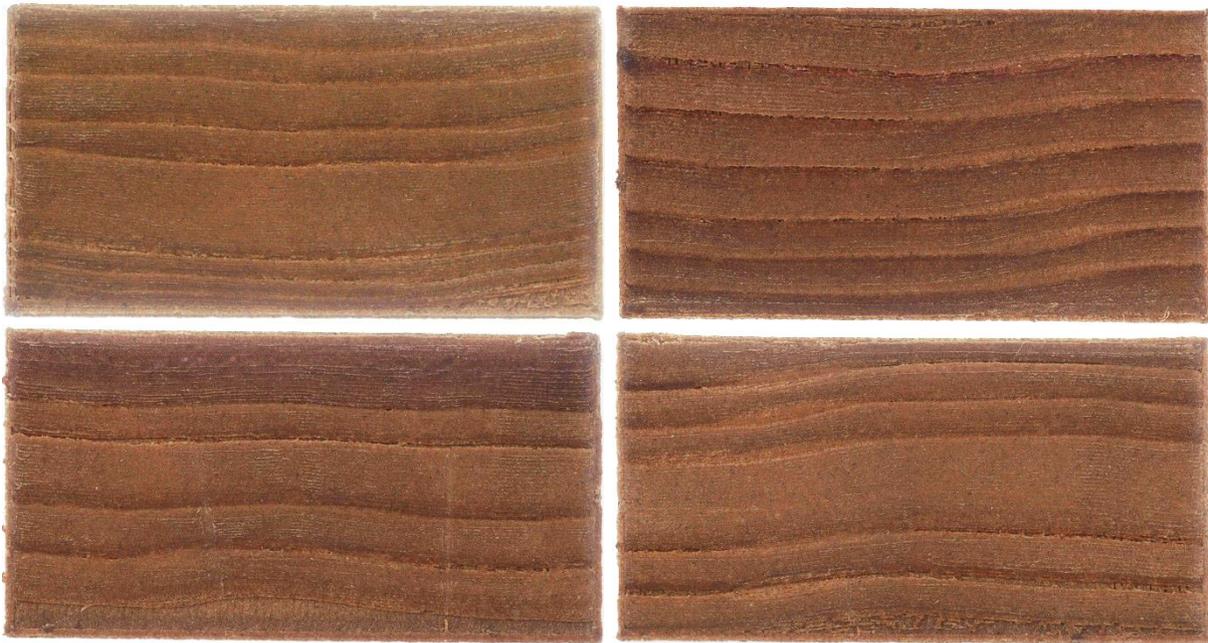


Figure 12: Wood grain aesthetic produced using 3D printer

Table 1 details the variables that were changed in the Processing script, which produced the prints in Figure 12.

Table 1: Average width of wood prints in Figure 12 and deviation parameter expressed in the Processing script

| Wood Print (in Figure 12) | Average Width (mm) | Width deviation parameter, <i>k</i> |
|---------------------------|--------------------|-------------------------------------|
| Top left | 5.0 mm | 20 |
| Top right | 6.7 mm | 10 |
| Bottom left | 7.0 mm | 10 |
| Bottom right | 6.3 mm | 10 |

Conclusion

An aesthetic of wood has been developed through the manipulation of the 3D printing process that normally presents a homogenous tone to the output. The creation of random variation along and across the grain was made possible through the generation of algorithms that were able to change the temperature of nozzle, control the extrusion pathway and control the feed rate in order to produce gradients and contrast that set a new paradigm as an aesthetic in its own right.

It is intended that the temperature controls only affect the exterior of a structural object. This is due to lignocellulosic materials experiencing rapid deterioration at temperatures above 250°C (Wolcott, 2001). This deterioration of wood fibre is likely to negatively affect the structural properties of the WPC. Hence it would be practical to separate the structural core from the aesthetic exterior.

Our future research into the field will explore the combination of internal structure and the exterior aesthetic skin in one process, which has the ability to reduce the assembly time and resources required for the construction of the product, as well as removing design limitations that arise as a result of wood laminate skins. As the purpose of creating an aesthetic during the 3D printing process is to be able to apply it to any 3D printable object's surface, this research presents an opportunity for future development of printer algorithms and process controls to make this possible.

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