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Abstract: Natural wood textures are appreciated in most forest products industries for their appealing visual characteristics including grain and color, but also their fine surface tactile sensation. The following presents an ultraviolet (UV)-curable inkjet technology printing 3D wood texture on wood-based substrate by image processing and surface treatment. The UV printing was created from scanned digital images of a real wood surface and processed in graphics software. The images were converted to grayscale graphics by selecting color range and setting the parameter of fuzziness. The grayscale images were printed as 3D texture height simulation on the substrates and coated by printing the color images as texture mapping. Based on these wood texture digital images, the marquetry art is also considered in the images processing design to increase the artistry of the printed materials. The medium-density fiberboard (MDF) coated printing marquetry surface replicate realistic natural 3D wood texture surface layers on wood-based panels and imitated the effect of handcrafted wood art works. This study proves that printing 3D texture surface material is creative and valuable with ecologically friendly, low-consumption UV-curable inkjet technology and provides a feasible and scalable approach in flooring/furniture/decorative architectural panels.

Keywords: 3D texture; UV inkjet; wood texture; image processing; digital fabrication

1. Introduction

Natural wood textures are appreciated in most forest products industries for their appealing visual characteristics including grain and color, but also their fine surface tactile sensation. Surface coated wood-based panels with decorative wood texture play a significant role as materials for construction, flooring and furniture elements in numerous interior and exterior applications [1]. However, the printing on laminates has traditionally been seen in predigital days as a low end product, because of it looks like fake wood or less value, and decorative papers with wood texture for laminates are typically produced using a rotogravure printing process, which requires numerous manufacturing steps to arrive at a new design. This rotogravure printing process is rather expensive and allows only economical production of decorative paper sheets for a specific wood texture design on a very large production scale [2]. Moreover, the process of impregnating the decorative paper and laminating the plate is not environmentally friendly or sustainable.

Recently, there is an increasing trend to print digitally wood grain patterns or give texture to building material and industrial products. Although a digital 3D PolyJet printing manufacturing workflow was presented to replicate both the surface color texture and the internal color texture of wood, the process comprising destructive tomographic imaging and voxel printing were too complex and time consuming to obtain and process the digital wood bitmap stacks [3]. While digital wood was printed by mixing resins of dissimilar durometers, the texture properties such as color, accuracy, and specularity are limited
by the mixing mechanics of photo acrylates and the printer resolution, respectively and did not replicate properly the characteristics of real wood. Wood texture generated by the natural growing process has its own unique characteristic. Various types of wavy grain, the striped figures on radial surfaces of wood with interlocked grain, and even moiré or checkered figures, are all resulting from systematically changing orientation of a meristematic cell layer under the bark. What is more, the changing give the nature wood a three-dimensional sensation roughly corresponding to the cell structure in the grain pattern on the cutting surfaces. Prior simulated grains made by printing have, however, had the disadvantage that they look flat and feel flat to the touch, and therefore lack a sense of being “natural”.

Inkjet printing is a relatively new technique in wood material industrial, allowing additive contact-free manufacturing based on digital image data [4,5]. Ink-jet is a non-impact dot-matrix printing technology in which droplets of ink are jetted from a small aperture directly to a specified position on a media to create an image [6]. One of the most abundant methods of inkjet technology is through inkjet printers that are widely used in the office and home. In fact, implementation of the technology is complex and the process requires multidisciplinary skills. It is the marriage of chemistry, physics, mechanical, and electrical engineering to address an even greater range of applications than can be printed digitally. Inkjet printing is viewed as a versatile manufacturing tool in materials fabrication in addition to its traditional role in graphics output and production. There are currently four main types of inkjet inks: phase-change, solvent-based, water-based, and UV curable [7]. While there are advantages and disadvantages for each type of fluid and hardware, UV curable inkjet inks, applied via piezoelectric drop-on-demand (DOD) print heads [8,9], are experiencing great growth. This is due to many advantages, such as being environmentally friendly, having higher productivity, and less waste and energy use, that UV curable inkjet inks bring to the process and to the end product. Most of all, using UV light instead of heat, the UV curing process instantly deposits a hardened layer of ink and directed adherence to both flexible and rigid materials [10]. The substrate versatility greatly widens the UV-curable inkjet industrial application for decorative surfaces on wood, metal, ceramic, textiles, plastics with colors, patterns, and textures. Wood is a very specialized market in industry inkjet printing and can take many applied forms, such as flooring, doors, and decorative panels [11]. The solution of UV inkjet provides a creative idea for the wooden products industry. Moreover, based on 2D digital fast and precision inkjet printing technology, the micro 3D stereo digital printing or 3D object accurate and fast production have been developed with UV curable inkjet technology [12,13]. The true colorful 3D objects as wood texture are solidified fast and bring 2D digital technology up to the 3D digital printing level.

Here, we present a UV-curable inkjet technology approach to print 3D wood texture surface layers on wood-based panels, which is not only applied for decorative purposes but also for practical purposes such as hiding surface damage and making uneven coatings invisible, even building 3D naturel wood surface texture structures. As a unified system, wood inkjet printing includes the hardware, the ink, and the interaction with the wooden substrate and so on. Once UV-curable inkjet technology has been chosen to print a wood textured decorative surface, there are additional considerations including image/information processing, printing methods, and surface quality. In this study, different from the traditional 3D printing driven by model cutting layers, UV printing was driven by digital images scanned from a real wood surface and processed in graphics software. The images were converted to grayscale graphic by selecting color range and setting the parameter of fuzziness. The grayscale images were printed as 3D texture height simulations on the substrates and coated by printing the color images as texture mapping. Based on the wood texture images, marquetry art is also considered in the design to increase the sense of value of the printed materials [14]. The different kinds of wood texture images are edited by graphic software just as hand-cut pieces of veneers to collage decorative patterns. The MDF coated printing marquetry surface with 3D natural wood texture imitates the effect of handcrafted wood artworks to enhance the artistic added-value. The overall aim of the study is to prove a feasible and scalable approach to print creative, realistic, valuable wood textures, to be applied in flooring/furniture/decorative architectural panels with the ecologically friendly, low-consumption, UV-curable inkjet technology.
2. Materials and Methods

2.1. UV-Curable Inks and Printer

UV curing chemistry for inks and coating can be used in printing 3D textures in the wood industry, due in part to advancements in hardware technology. The UV inkjet flatbed printer (HT2512 UV FG, Shenzhen HANDTOP TECH CO, Ltd., Shenzhen, China) used in this test are deferent from the inkjet-style 3D printers that have been successfully utilized in the manufacture of internal structure parts by selective laser sintering and fused deposition modeling. While a 3D wood texture is printed by a 2D UV-curable flatbed printer with higher print speed, reliability, and resolution in industrial printing market. Obviously, UV curable inkjet compositions formulated for use in two-dimensional (2D) inkjet printers are typically formulated differently than compositions for 3D Poly-Jet.

The UV curable ink formulas used in flatted UV printer are comprised of the following material: monomers/oligomers, colorants (pigments or dyes dispersed or dissolved in a reactive carrier), photoinitiator, and additives [15], as shown in Figure 1. Reactive monomers and oligomers make up the base of an inkjet formula, giving the fluid most of its properties. Many additives are needed to realize all quality aspects, including surfactants, in-can stabilizers, adhesion promoters, etc. These materials must allow free radical additions to occur [16]. The photoinitiators form radicals upon UV exposure and these in turn start up the polymerization of the monomers. The UV ink derives its color from the pigment dispersion. The radical polymerization chain reaction that occurs consists of at least four steps: initiator radical formation, initiation, propagation, and termination [17], which is shown in Figure 2. The basic ink set for printing 3D wood texture in the test included five primary colors: cyan, magenta, yellow, black, and white (Arigi UV HD1 ink set, Agfa NV, Belgium).

![Figure 1](image1.png)

**Figure 1.** UV-curable ink comprises the compounds: monomers, colorants, photoinitiator, and additives.

![Figure 2](image2.png)

**Figure 2.** (a) Schematic representation of UV ink, being jetted onto a substrate; pigment particles (blue), photoinitiator (red) and monomers and oligomers (gray). (b) The UV light degrades the photoinitiator into free radicals, which chemically react with the monomers and oligomers; (c) photopolymerization continues until all monomers and oligomers have reacted; and (d) solidified UV-curable ink with captured pigment particles.
2.2. Digital Image Design

Flat scanning is a very common image acquisition method. A charge coupled device (CCD) technology scanner (Phantom 9900XL, Microtek Co., Suzhou, China) was used to scan wood samples to digitize wood texture in the tests. Due to the inherent technical advantage of camera-based scanning technology, the color depth and the ability to recognize the nuances of gradients is superior on CCD scanners, the color gamut is much wider, and color fidelity is greater. The scanner are able to image raised or uneven surfaces with depth of field [18]. This is very helpful when scanning the wood surfaces with 3D grain. These scanning systems are designed to capture textures in wood [19], so that printing reproductions feature the same lifelike quality as their natural counterparts. Therefore, collecting samples of valuable wood and applying special finishing effects are used as scanning samples to obtain very beautiful wood texture images, as shown in Figure 3. These wood images are used directly in wood products printing, and also saved as wood material stock images for special designs. Most importantly, in order to increase the product’s added value, the wood texture design of the surface image is more meaningful in order to create an artistic sense.

![Figure 3](image.png)

Figure 3. (a) Natural color hinoki, (b) brushed oak (c) antique finished elm (d) distressed Pterocarpus, (e) Phoebe (f) Dalbergia, (g) camphorwood, and (h) burl.

Both veneered marquetry and intarsia are art forms that utilize the beauty of wood grain [20]. These crafts both apply wood pieces according to each one’s color and texture to a structure to form decorative patterns, designs, or pictures. According to the rules of this craft, the pattern outlines are made by cutting or sawing, and the figure is filled with colorful wood to create an image in marquetry or intarsia wood pieces. The design process is not limited by the defects and size of natural wood, when using digital reproductions of rare wood to create an image with a high-value feeling. This digital marquetry or intarsia images printed on wooden substrates by UV inkjet copy the real wood grain and simulate the astonishingly craft patchwork, as shown in Figure 4.
2.3. Printing Substrate

Based on digital wood texture images, UV printing technology was used to create 3D texture on the substrate surface to form a solidified UV-curable ink layer structure. The substrates used in the tests were the medium-density fiberboards (MDF). There were two kinds size MDF: the 18 × 50 cm\(^2\) rectangular ones were used for printing one special wood texture and the 60 × 60 cm\(^2\) square substrate with installation notches were used for printing the marquetry designing wood texture in tests. All the surface of MDF substrates were coated with white primer (per layer roll coating, 20 g/m\(^2\)) and sanded with 180-grits sandpaper.

2.4. Mapping Printing

Texture mapping is a powerful technique that has traditionally been used to add realism to computer graphics images [21]. In its basic form, texture mapping lays an image (the texture) onto an object in a scene. More general forms of texture mapping generalize the image to other information; an “image” of altitudes, for instance, can be used to control shading across a surface to achieve such effects as bump-mapping. Texture mapping provides a way to realize the 3D realistic wood texture technology by UV inkjet printing. Texture mapping printing makes use of images to shape the bump surface, reducing the 3D model complexity while enhancing realism, opening new ways to visualize large amounts of wood texture details in a comprehensive fashion.

In natural wood, the dark grains shown in Figure 5a) are slightly dented due to the wood’s changing seasonal growth characteristic, this results in the three-dimensional sensation that wood gives when touched. The grayscale image (Figure 5b–d) as the height image reverses grayscale darkness from the original image [22]. For implementing a texture mapping printing process, the height images for shaping and the color image for surface display are to be printed together. The color grain is mapped (printed) on the 3d wood grain model (bumpy texture), which is created with the height image by UV inkjet printing. Texture mapping printing makes use of images to shape the bump surface, reducing the 3D model complexity while enhancing realism, opening new ways to visualize large amounts of wood texture details in a comprehensive fashion.

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shallow, the effect of Figure 5c was most characteristic and close to the actual textural effect in the visual image. In the test, Figure 5c was converted in white spot channel, as shown Figure 5e.

**Figure 5.** (a) An original, RGB scanning image of an elm board sample. (b) Grayscale image: fuzziness parameters 50. (c) Grayscale image: fuzziness parameters 100. (d) Grayscale image: fuzziness parameters 150. (e) White spot channel effect.

The grayscale images converted to white spot channel printing simulate layers of 3D layer-by-layer printing and relate to printing settings of saturation and volume of ink output. The darker the pixel is in the grayscale image, the more volume of white UV-curable ink would be printed and deposited on the fixed place of the substrate. The drop impact on the substrate converts the spherical drop into a bump dot, its size mainly depends on its volume, and the physicochemical properties of both substrate and ink. As shown in Figure 6, the black/white/gray dot in the image determines the different volumes of inkjet droplets deposited on the substrate, which was the image pixel controlled the height shape. Moreover, the grayscale image information in the white spot channel was set with a solidity of 100% and printed white ink three times, so the height difference is broader and more three-dimensional, forming a stereo texture corresponding to the grayscale image’s color information. The color image of wood the texture, exactly pixel-to-pixel aligned with the height image, is more inclined to express the realism of the perceived 3D surface texture. The process schematic diagram is shown in Figure 7.

**Figure 6.** (a) Black, white, and gray dots in the grayscale image, (b) ink droplet curing on substrate, and (c) 3D texture formation by UV-curable ink deposition.
3. Results and Discussion

The wood texture was printed on the surface of MDF using the process described in the preceding section, and shown in Figures 8 and 9. Under natural light, the MDF board with elm grain is very vivid and realistic in color, texture, and touch. To enhance the printing value, the marquetry image was printed on the 60 × 60 cm² square MDF board with installation notch, so that it can be used for floor or wall decoration. As shown in Figure 9, it looks more like hand crafted work due to the simulated complex manual patchwork. The fidelity of printed surfaces comes from the high-precision scanning that is being printed very well to resemble its nature color, and the perfect three-dimensional effect printed layer by layer. In particular, in the greyscale operating mode, dynamic variable drop technology can produce drops of varying sizes within a single image file, and the small drop size delivers the highest image quality for fine color gradients. Thus, using a UV-curable inkjet printer with variable drop grayscale head, the wood texture printing derives an image quality consistent with small drop high resolution imaging. The gloss and texture are closer to people’s perception of real wood, as in the original image [23,24]. The schematic process shown in Figure 10 reveals that a real wood texture is replicated by scanning, processing, and UV printing.
Figure 9. Printing marquetry designing on MDF: (a) square digital printing marquetry board with installation notch, (b) details of printing 3D wood texture, and (c) replicated wood marquetry.

Figure 10. (a) A wood texture, (b) color image scanned, (c) grayscale image scanned, (d) white UV-curable ink overlap drove by grayscale image, (e) color image texture mapping printing on the white ink deposition model, and (f) a replicated printing wood texture.

The 3D wood texture was printed on the substrate, which ranges from MDF, laminate, chipboard, and wood board. The flatter the surface of the substrate, the better the printing effect, although the no-touch inkjet printing can cover up some defects on the surface of the substrate. The MDF with a flatter surface is more conducive to the UV flatbed printing, and adds more value in applications relatively. However, the MDF substrate with a darker color, also the wood fiber on surface, affects the color rendering effect by the direct printing. Inkjet substrates typically contain a special thin coating on the top enabling high print quality. A white primer coating on the MDF surface played this role in the tests. When a drop landed on the substrate, UV light converted instantly the spherical drop into a bump dot adhered on the surface medium. The UV-curable ink deposited layer by layer to shape the simulated 3D wood texture on the substrate surface, becoming a solidified UV-curable ink layer structure shown in Figure 11.
The wood texture can be scanned at 300 dpi image resolution and exported at 1440 dpi print resolution in a multipass model. The conversion of color images to grayscale images is the key to maintaining the color of the 3D wood grain and the stereo texture printed with the grayscale image to be completely matched. Nevertheless, the digital camera scanning technology enables simultaneous captures of 2D and 3D color image structures simulation. A scanner with a light emitting diode (LED) light system and Professional International Color Consortium (ICC) profiles can guarantee the best scanning results with the most color fidelity [25]. Moreover, using special light modes, like a texture effect or light angle devices, the details of the objects surface can be captured with natural accuracy [26]. The RGB scan and stereo scan are separate, but the images are absolutely matched during the scanning process. Since the required images can be obtained technically, finally as digital information to support this way of mapping printing, there is a significant benefit to create a basic wood material image stock with texture height information. This wood texture stock shared by designers will help the customer to fit their specific design requirements in wood the products market such as doors, floors, and decoration.

Due to inkjet printing’s outstanding jetting behavior and color management, the high image quality and the perfect details of natural wood pores and the fine colors have been replicated and displayed in the test, but the material’s physical performances are also required to meet the application standards [27,28]. During this process, the liquid UV-curable ink drop applied to the MDF substrate, and a subsequent phase change instantly transformed the liquid into a solid by a number of chemical reaction mechanisms under UV light. In this case, there are two interface relationships that can affect the physical performance of the printed 3D texture surface, as can be also seen from the structure schematic of printed 3D wood texture. First, solidification occurs postdeposition, and the printed pattern must retain some stability in the liquid state prior to solidification, between the printed drop and the substrate prior to attaining the desired texture structure. Second, 3-D wood texture structures are produced by overprinting sequential layers, requiring the drops to overlap to form continuous features. The interaction between a drop and a solidified deposit is not absolutely the same in quality when deposited on a substrate. Although UV-curable ink has excellent adhesion, and great abrasion and chemical resistance, the printing material surface’s physical performance (adhesion, hardness, and wearability) is not only affected by the capability of the ink, but also the interactions between the ink layers and substrate [29]. Thus, these interactions of inkjet flow with structured surfaces are meaningful to be further researched for improving the material’s physical performances.

4. Conclusions

The image processing and printing workflows described in this article can be readily used for replicating real wood surface texture. Since the study was inherently digital, the original wood samples were significant to be prepared and scanned to create the digital material stock. The wood samples through mechanical treatment, coloring, and finishing have aesthetic qualities of clear and fine grain, and are scanned and saved as digital material resources. Based on high-quality design and printing, which undoubtedly improves the added value of substrate materials with replicated wood surfaces.
Particularly in the case of printing marquetry art in the study, the wood texture images were edited and filled in the path graphics, then printed on relatively low value MDF to simulate the handmade wood artworks that traditionally require a lot of manual labor. Though the printed marquetry works were edited and replicated from digital material stock, they have fine textures and apparent hand-crafted beauty, and achieve the maximization of printing value.

This work focused on digital printing reproducibility of 3D wood texture, especially the real wood perception on wood material. The wood texture can be scanned at 300 dpi or more image solution and export at 1440 dpi print-solution in multipass printing mode (printer hardware and software setting), which ensure the delicate color and rich layering of the printed wood grain texture. Moreover, this study has shown the ability to extend 3D wood texture structures to design new styles of wood products along with the potential for a variety of applications. UV-curable inkjet printing derived from digital image information achieves individual design ideas in a range of sizes and styles, with multipass, large color gamut and high color vibrancy. Coupled with hardware technology and ink chemistry, this technology, a non-contact, additive patterning and directly writing of the ink deposition approach, has many attractive features in wood area applications: the reduction of manufacturing costs, provision of higher quality output, conversion of processes from analogue to digital, reduction in inventory, the new ability to process larger, smaller, or more flexible, fragile, or non-flat substrates, reduction of waste, mass customization, faster prototyping, and implementation of just-in-time manufacturing. Thus, the testing and simulation integrates the multiple technology factors in the system, predicts their behavior, and informs the production of designed materials.

The development of technology has allowed us to expand the possibilities of business problems: a material that can transform and shape our desires, expressions, and sensory characteristics. The flexibility of designed materials, such as touch, color, and transparency, also promotes its return to culture, sense, and the level of communication. From the recognition of sensory psychology, the application of natural wood textures in furniture and wood products has always been the subject of surface decoration for the purposes of the sensory experience that is similar to the actual wood surface characteristics. It is precisely this kind of emotional, life, and cultural need that has driven the development of this scientific research.

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