J Wood Sci (2005) 51:270–273
DOI 10.1007/s10086-004-0637-z

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Evaluation of surface smoothness using a light-sectioning shadow scanner

Received: February 16, 2004 / Accepted: April 16, 2004

Abstract A new type of sensor for rapid three-dimensional evaluation of surface geometrical properties is presented. Light emitted with a fixed small angle to the surface plane by a projector is directed into the measured surface. A curtain installed in the light path close to the surface creates a shadow on the measured surface. The shape of the border between bright (highly lit area) and dark (shadow area) is a profile section of the surface. The camera installed over the measured surface captures an image of the border and a digital signal processor using image analysis techniques digitizes the profile section. The shadow scanner method evaluated here could be used for rapid and accurate scans of surfaces of various porous materials, particularly wood, veneer, paper, fiberboards, leaves, and similar materials in both laboratory and industrial applications. The simplicity of the sensor is an advantage because it makes the system easy to maintain, resistant to breakage, and inexpensive. Its straightforward nature and high accuracy enables the method to be utilized for on-line measurement, and therefore it is suitable for industrial application.

Key words Wood surface · Roughness · Smoothness evaluation · Shadow · Light sectioning

Introduction

An effective method for the evaluation of surface roughness in industrial environments has been sought for some time. Some devices (mostly laser based) capable of describing surface roughness are already available for high precision applications. However, such devices are both very expensive and overly accurate for application on porous biomaterials such as wood. Moreover, measurement speed and the fragility of the techniques make them appropriate only for laboratory-based metrology. They are not suitable for the industrial environment.

Various physical phenomena such as mechanical, optical, pneumatic, ultrasonic, electric, or temperature detection approaches can be used as principal components for the measurement.[1–3] The techniques most capable of determining surface smoothness in an industrial environment are those that are noncontact, with reproduction of the profile. Within the above group of methods belong various types of optical profilometers (mostly laser based),[4] microscopes, image analyzers,[5] imaging spectrographs,[6] interferometers,[7] fiber-optic transducers,[8] white light speckles,[9] laser scatters,[10] and optical light-sectioning systems.[11]

Surface smoothness can be evaluated in one, two, or three dimensions (1D, 2D, or 3D), but most methods are based on 2D measurements. Utilization of 3D techniques creates new areas for mathematical evaluation of the surface, more accurate prediction of its performance, and better understanding of the varied phenomenon affected by the surface geometry. Characterization of surfaces using 2D profiles is rewarding, but has important limitations. Depending on the application, the information regarding an area of a surface provided by a sensor that does not reproduce the profile (such as pneumatic, capacitance, ultrasound, optical reflection, or scattering) could fulfill requirements. However, these only provide an average value over the surface area and much quantitative information cannot be extracted. Some surface properties such as anisotropy cannot then be measured and quantified, and assessment of the total surface area is also impossible in one pass of the sensor.

The goal of the present study is to develop an accurate scanning system capable of rapid three-dimensional evaluation of wood surface smoothness, dedicated to on-line measurement.

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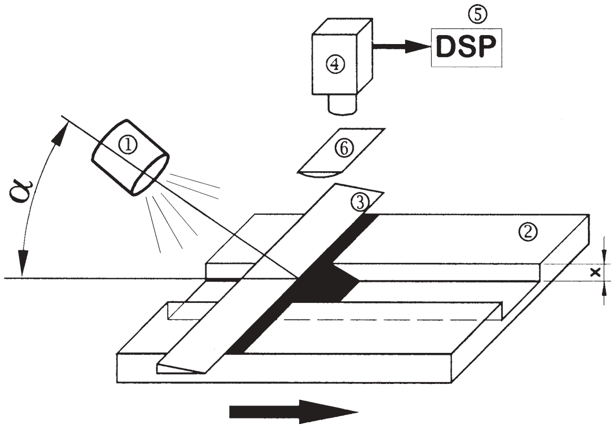

Fig. 1. General schematic of the shadow scanner. *DSP*, digital signal processor

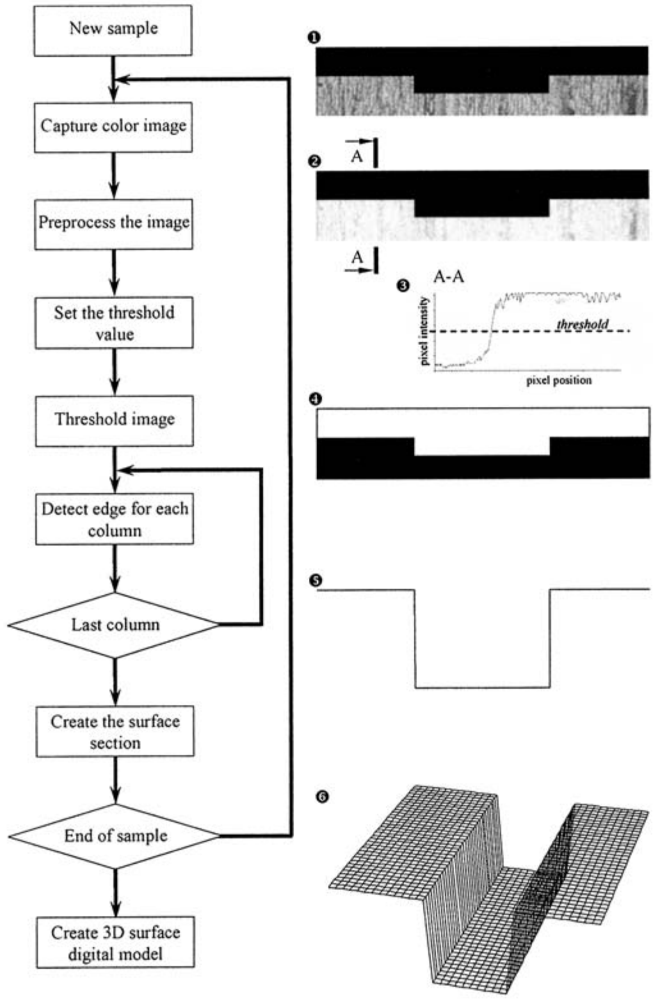

Fig. 2. Algorithm for signal processing for the shadow scanner

Materials and methods

Set-up

The system consists of two major components: experimental hardware and software. The hardware (Fig. 1) consists of a parallel light projector, curtain, and charge-coupled device (CCD) video camera. Depending on the application and the light-sensitive CCD detector employed, the light emitted can be monochromatic or multiwavelength. With reference to Fig. 1, parallel light emitted by the projector ① is directed onto the measured surface ② at a small fixed angle to the surface plane (α). In the light path and close to the surface, the curtain ③ is installed. The curtain creates a shadow on the measured surface, and the shape of the border between bright (highly lit area) and dark (shadow area) is a profile section of the surface. The camera ④ installed over the measured surface captures an image of the border and the digital signal processor (DSP) ⑤ uses image analysis techniques to scrutinize the profile section. A single measurement provides information about one section of the surface, but by moving the workpiece under the sensor, the next section can be scrutinized. By continuing this process a number of times, the total sample area can be examined and a 3D numerical model of the surface shape can be created. Cylindrical lenses ⑥ are applied to improve the optical resolution of the system.

The value of the angle between the light direction and the measured surface plane (α) depends on the expected measurement range and is large when the required range is high. Conversely, the resolution of the sensor increases when angle α decreases. If the surface inclination is higher than the angle α, some misrepresentation of the measured profile occurs.

In the method presented here, the profile section corresponds to the edge defined as the border between the shadow and the lit surface.

Signal processing

Special software is an integral part of the proposed system. This software is capable of supervising all elements of the system, acquiring the data, creating a 3D surface map from the profile sections, processing/filtering the data, and expressing the surface geometry using standardized parameters. The algorithm for the creation of the 3D model of surface is presented in Fig. 2.

Measurement starts with the trigger provided by a rotary encoder, switch, or controller. The trigger signal initiates an image acquisition process. One section of the measured surface is scrutinized in each cycle. The CCD camera (analog in slow applications or digital when rapid measurement is required) captures one image of the measured surface including the shadow zone ❶. Depending on the application, the image could be monochromatic or color. The image from the camera is then transferred into the DSP (specialized vision system unit or personal computer) for future processing. The components of the signal processing procedure could include various operations such as: extraction of the region of interest (ROI) to minimize the amount of data to be processed by the microprocessor, extraction of the most meaningful color plane (R/G/B or H/S/I), filtration of the image for elimination of any unacceptable signals from the source image, contrast corrections, or any other operations to be executed on the image with the objective of improving the quality of information provided. As a result, a monochromatic image of the shadow border ❷ is created, and is ready for further segmentation.

In the next step, the image is segmented (binarized) into two sections corresponding to shadow (pixels with low intensity) and illuminated areas of the measured surface (pixels with high intensity). Threshold function offers the simplest and the most effective separation of these areas. The boundary value of the threshold can be obtained dynamically through histogram analysis, or the threshold can be preset by the operator before the measurement using an intensity section of a random column taken from the source image ❸.

Next, the border between the shadow and illuminated surface must be mapped. The edge detection algorithm could be applied for this purpose. A single calculation of the edge position provides the location of the pixel for only one column. Therefore, for the total surface section ❹, the edge is detected for each column of the image, one by one in a loop formula. Numerical coordinates of the 2D section of the surface ❺ are thus obtained. If a 3D model of the surface is required, the workpiece must be moved under the sensor a certain distance and the next section can then be scrutinized. This process must be continued to the end of the measurement length, and all operations are therefore performed in the loop. A scan of the total sample area can be made by repeating this process a number of times. Finally, the matrix of data obtained can be visualized on a graph ❻ and used for future calculation/analysis of surface smoothness indicators, or it can be analyzed in other ways depending on the application (e.g., surface defect detection).

We found experimentally that use of the red plane for binarizing the image gives excellent results. We used a manual threshold, which was set depending on the workpiece condition (generally surface color). Calibration of the system was performed using samples of known surface shape. Images of the shadow sections of the triangular profiles with varied height of irregularities were evaluated with the preceding algorithm. After that, the range of pixels obtained by the image analyses was correlated to the value of the profile height. High accuracy of the shadow scanner was confirmed by comparison with corresponding profiles acquired by a stylus. Gray images were used for visualization of the evaluated surfaces where the gray intensity of each pixel represents elevation of the surface.

Results

Three-dimensional maps of the wooden surfaces scanned using the shadow profilometer are shown in Figs. 3–5. Figure 3 presents images of two surfaces of glued lumber

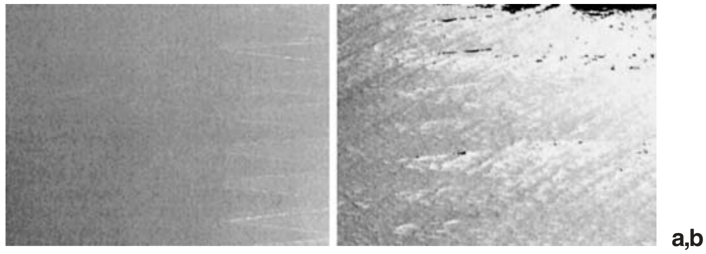

Fig. 3a,b. Surface of wood after sawing with circular saw at varied feed speeds. **a** 1 m/min, **b** 10 m/min

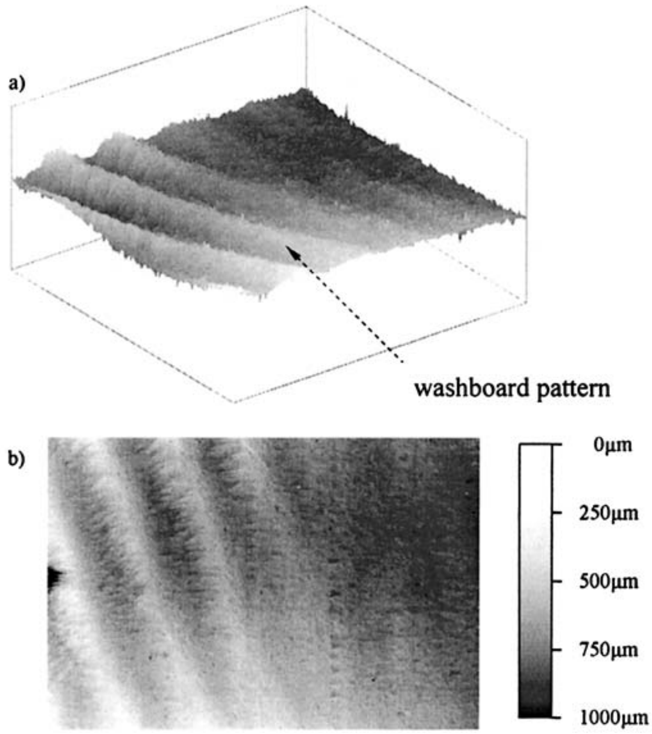

Fig. 4a,b. Examples of the profiles scanned from the surface containing washboard pattern generated during band sawing. **a** Three-dimensional view, **b** top view

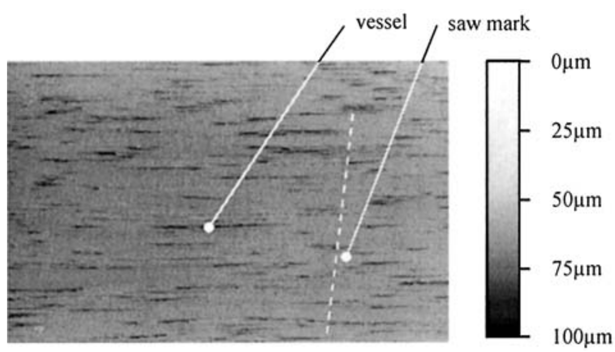

Fig. 5. Example of the surface profiles scanned from the hardwood surface after cutting on a sash-gang saw

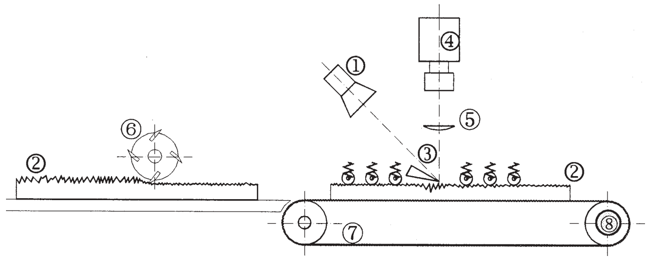

Fig. 6. Setup for on-line evaluation of lumber surface after planing operation; ① light source, ② workpiece, ③ curtain, ④ CCD camera, ⑤ cylindrical lenses, ⑥ cutter head, ⑦ conveyor, ⑧ rotary encoder

created by a circular saw when cutting speed was kept constant, but feed speed varied between 1 and 10 m/min. Intuitively, when feed speed is low, the surface is smooth. This was confirmed in the experiment. The intensity of each pixel in Fig. 3 indicates the height of irregularities in its particular coordinates. Dark pixels indicate valleys and bright pixels represent surface peaks. When the intensity variations (differences between bright and dark pixels) are small, the surface is smooth (Fig. 3a). Conversely, high contrast between pixels indicates elevated roughness (Fig. 3b). The resolution of the sensor was good enough to distinguish tiny saw marks created during cutting. The zigzag pattern on both surfaces corresponds to the finger joints.

The shadow scanner was able to accurately scrutinize very rough surfaces (washboard pattern) produced during unstable processing on a band saw [workpiece: sugi (*Cryptomeria japonica*), ~12% moisture content]. Both smooth and wavy parts of the surface were clearly differentiated (see Fig. 4).

Lastly, it was found that quite smooth hardwood surfaces [kusia (*Nauclea diderrichii*), ~12% moisture content] were also precisely reproduced by the sensor. Figure 5 is a top view of the wooden surface processed using the sash-gang saw. The dark areas on the image indicate deep anatomical elements of the wood (vessel). Close observation of Fig. 5 shows that tiny saw marks (a result of the machining) are also visible as a regular pattern of dark parallel lines.

The system can be used to detect various unwanted defects that appear on the surface of the product during manufacturing. An example of the setup dedicated for defect detection of the planed surface is presented in Fig. 6. The workpiece after machining on the planer is scanned by the shadow profilometer. To reduce an effect of the machine vibrations the measured piece lays on a conveyor. The system proposed evaluates surface imperfections by comparing the surface roughness scanned to the acceptable roughness of the final product.

Conclusions

The shadow profilometer method evaluated here could be used for rapid and accurate scans of the surface of various porous materials, particularly wood, veneer, paper, fiberboards, leaves, and others. This new type of sensor allows rapid three-dimensional evaluations of surface geometrical properties in both laboratories and industrial applications. The resolution of the sensor is appropriate for both isotropic and porous biomaterials. The simplicity of the sensor is also a great advantage because it makes the system easy to maintain, resistant to breakage, and inexpensive. Surfaces are scanned without contact; thus, surface damage during measurement is avoided. Its straightforward nature and high accuracy enables the method to be utilized for online measurement, and therefore it is suitable for industrial application.

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