Adaptive milling of solid wood furniture workpieces: analysis of the extended approach capabilities

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Abstract. An extended approach to improve adaptive milling of solid wood workpieces is described. It is based on the joint usage of two physically different methods: non-contact ultrasonic scanning of the workpiece body and optical recognition of the wood fibers direction on the workpiece surface. To implement the proposed approach, it is necessary to change the existing technological route of furniture workpieces processing. A stage before the milling operation should be included. This stage involves the sequential execution of ultrasonic scanning, computer processing, and optical recognition of the obtained data. It allows us to determine the wood density, the internal defects localization, and the direction of wood fibers. Computer processing involves the usage of a virtual orthogonal grid. This grid covers the workpiece surface, on which the trajectory of the milling cutter is projected. The projection of the milling path is represented by the set of cells. The gathered information about the wood properties is suggested to use for the adaptive selection of the important equipment technological parameters, such as the feed rate and the cutter rotation frequency. Varying of these parameters values and considering the physicomechanical properties of wood at the processing area allow us to improve the milling quality.

1. Introduction

The forest is a renewable source of wood, which is a valuable raw material for many uses. In particular, solid wood and materials based on it (wood-based panels) are widely used in furniture manufacture. One of the most important consumer properties of furniture is aesthetics, along with functionality, ergonomics, and reliability. The consumers are interested in the furniture based on original design decisions, made of solid wood, and including decorative elements. A relief on the furniture surface is one of the most popular decoration approaches used in furniture manufacture. It is created by the furniture workpiece milling.

The quality of wood milling depends on many factors. The most important factors were experimentally established. They are direction, feed rate, cutter rotation frequency [1, 2], wood species (hardness) [3], the cutting tool degradation, and others [4, 5]. Based on this, it is reasonable to use adaptive milling technology in the processing of solid wood furniture workpieces. It can be applied via the computerized numerical control (CNC) machines.

Other important factors, such as feed rate and cutter rotation frequency, must be taken into account for the adaptive milling in addition to the optimal technological parameters selecting. For example,
the decorative milling is characterized by the complex geometric relief creation on the workpiece surface. When it is performed, the anisotropy of wood should be considered. It is expressed in its mechanical properties difference for different directions and depending on the angle between the direction of the acting force (working tool) and the direction of the wood fibers. The results of theoretical and experimental studies on the interaction of a working tool and wood during milling along and across the fibers are given in the publications [6-8].

The publication [9] contains the research results which represent the dependence of the milling quality on the angle between the direction of the wood fibers and the milling cutter. The developed mathematical model of interaction between the cutter blade and the wood surface is implemented as a computer program performing simulation (computational experiment). The simulation results interpretation and comparison with experimental data gave us an analytical dependence. The milling cutter feed rate is a function of the wood fibers orientation angles and the path of the cutter in the local processing area. The optical recognition of the wood surface macrostructure allows us to determine these angles.

Solid wood furniture workpieces have the same features as every natural wood (for example, knots, cracks, rot, etc.). For the deep relief wood milling (3D milling), it is necessary to take into account the internal defects along with the surface macrostructure. Therefore, one of the promising leads for improving adaptive 3D milling is the development of an advanced approach. It should take into account both the surface macrostructure and defects located in the inner region of wood. Many non-destructive testing (NDT) methods are known to measure wood quality. They are acoustic and ultrasonic scanning, microwave testing, near-infrared testing, radiography scanning (X-ray, gamma-ray) [10]. Ultrasonic scanning is NDT method based on the propagation of ultrasonic waves in the tested object or material [11].

The method of non-contact ultrasonic scanning can be used to localize defects in the workpiece body. It allows detecting heterogeneous areas that differ in density. This method is one of the most technologically advanced non-destructive methods to inspect various materials, including wood.

As mentioned above, to improve the milling quality is necessary to ensure the possibility of changing the cutter feed rate and rotation frequency. It depends on the wood properties in local processing areas. Following wood properties should be taken into account: the density and anisotropy, and the presence of defects in the workpiece body.

Thus, the extended approach to improve the adaptive 3D milling involves a preliminary stage. Its purpose is to determine the wood density, the localization of internal defects, and the direction of wood fibers. For this purpose, the combination of two physically different methods is suggested to use. Non-contact ultrasonic scanning of the workpiece body is performed first. Next, the optical recognition of the wood fibers’ direction on the surface of the workpiece should be done. The information obtained after these methods were executed can be used further to adjust the control program for the CNC.

2. Materials and research methods

2.1. Non-contact ultrasonic wood scanning method

The ultrasound usage has become widespread and underlies many experimental studies of the various materials properties, including wood. The main elements of the ultrasonic scanner are a pair of sensors (piezoelectric transducers), which act as a radiator and receiver. The emitter generates an ultrasonic pulse automatically or by the influence of an external source. This pulse propagates through the material and reaches the receiver. In this case, the pulse time is measured and is used to calculate the studied parameters of the material.

Currently, both contact and non-contact ultrasonic methods are used. The contact method involves the usage of a liquid binder (for example, water, gel, or oil), so ultrasonic waves with sufficient energy can propagate from the transmitter to the receiver through the sample [12]. However, the applying of a binder on the sample surface requires additional time. Additionally, it is often unacceptable for the
wood due to its high hygroscopicity because of the porous structure.

In such cases, the non-contact ultrasonic method (ACU – air-coupled ultrasonic) is preferred. It uses ambient air between the emitter and the sample or between the receiver. In the second case, the sample is used as a binder [13]. Only a small part of the acoustic energy can penetrate the sample due to the large difference in the acoustic impedance of air (457 Rayl) and wood (1.57×10^6 Rayl). It causes high losses due to the reflection of ultrasonic waves [14]. It is the main disadvantage of the ACU method. So this method was recently used mainly for studying wood samples whose thickness does not exceed 30 mm [15]. Currently, this limitation has been largely overcome by increasing the power of ultrasonic radiation and the sensitivity of the sensors [16]. It allows us to significantly increase the thickness of the studied wood samples [17].

In ultrasonic research, the relative positions of the emitter, receiver, and sample can be different. It provides the following operating modes [13]: normal through-transmission, slanted through-transmission, plane wave, and pulse-echo. It should be mentioned, that the most often used mode is the normal through-transmission.

The diagram of the non-contact ultrasonic examination of a furniture workpiece is shown in figure 1. It is similar to the contact ultrasonic monitoring diagram of the wood density based on a temporal shadow method [12].

![Figure 1. Schematic diagram of the study of wood using the non-contact ultrasonic method: 1 – alternator; 2 – an emitter; 3 – furniture workpiece; 4 – receiver; 5 – amplifier; 6 – pulse arrival time meter.](image)

The following items are sequentially determined during the ultrasonic control of the furniture workpiece wood density [12]:

- ultrasound delay time \( t_d \) in piezoelectric transducers and air layers in the benchmark sample. This time characterizes the sensors and does not depend on the wood properties;
- time of signal passing through the wood. It is the difference between the signal passing total time and the delay time;
- propagation speed of ultrasound in wood:

\[
\nu = \frac{h}{t - t_d},
\]

where \( h \) is the wood thickness, \( m \); \( t \) is the transit time of the ultrasonic pulse from the emitter to the receiver, \( s \); \( t_d \) is the pulse passing time through acoustic delayers: prisms or protectors, air layer, \( s \).

The method for determining the density and hidden wood defects localization is described below. It uses non-contact ultrasonic scanning and involves the imposition of a «virtual» rectangular (orthogonal) grid on the surface of the furniture workpiece. The size of the grid cells is 10×10 mm. The mill trajectory is «projected» on the surface covered by the grid and cells. The local processing area is determined by comparing the coordinates of the trajectory points and the coordinates of each cell vertices (figure 2).
Figure 2. The image surface of the furniture workpiece with a superimposed virtual grid and the projected path of the cutter (dashed line).

An ultrasonic scanning generates an array of values. These values can be used as a numerical characteristic of the workpiece wood bounded by the corresponding cell. It is known that when the wood density increases, the speed of sound propagation increases. Thus, if the density of wood sharply (abnormally) increases in comparison with the density of the surrounding areas, then this area probably has a knot. It can be covered by one or more grid cells.

Conversely, when the density decreases abnormal, it is very likely that a cavity or rot will be found in this area. The gathered characteristics of the workpiece are further used for adjusting the control program for the CNC machine. It allows us to select optimal milling parameters such as feed rate and cutter frequency.

2.2. Method for optical recognition of the wood fiber direction

The optical recognition of the wood fibers direction is used as a part of an enlarged algorithm, the block diagram of which is shown in figure 3. This method determines the surface macrostructure of the furniture workpiece. In particular, it allows us to identify the direction of the wood fibers.
Figure 3. Block diagram of the enlarged algorithm for the optical recognition of the wood fibers direction of the furniture workpiece.

Figure 4 illustrates the sequence of actions when the optical recognition method to find the direction of fibers is used in the local processing area. This area is represented by a square bounded by a grid cell [9]. In the first square (figure 4a), the arrows show the coordinate axes. They represent the
intensities $I(x)$ and $I(y)$ (figure 4b). The second square (figure 4e), represents the reduced version of the first square. The arrow shows the calculated direction of the wood fibers.

Using a digital image of the selected square, the functions $I(x)$ and $I(y)$ are determined (figure 4b). They represent the dependence of the image intensity (either the total intensity or one of the RGB additive model channels) on the coordinate along two orthogonal axes $x$ and $y$. The center of the axes should be located in the center of the square. A quantitative estimate of the periodicity in each direction is performed using the discrete Fourier transform for the functions $I(x)$ and $I(y)$, which allows obtaining the spectra $w_x(k)$ and $w_y(k)$ (figure 4c) [9]:

$$
\begin{align*}
 w_{ik} & = \sqrt{\left(\sum_{i=1}^l (I_{i_0+i,j_0} - I_{0x})\cos(\omega k)\right)^2 + \left(\sum_{i=1}^l (I_{i_0+i,j_0} - I_{0x})\sin(\omega k)\right)^2}; \\
 w_{jk} & = \sqrt{\left(\sum_{j=1}^l (I_{i_0+i,j_0} - I_{0y})\cos(\omega k)\right)^2 + \left(\sum_{j=1}^l (I_{i_0+i,j_0} - I_{0y})\sin(\omega k)\right)^2},
\end{align*}
$$

where $I_{ij}$ is the intensity of a pixel with indices $i$ and $j$; $i_0$ and $j_0$ are indices of the center of a square; $\omega$ – trigonometric factor; $k$ is the inverse distance; $I_{0x}$ and $I_{0y}$ is the average intensity in the $x$ and $y$ directions, calculated using the following formulas:

$$
\begin{align*}
 I_{0x} & = \frac{1}{2l+1} \sum_{i=1}^l I_{i_0+i,j_0}; \quad I_{0y} = \frac{1}{2l+1} \sum_{j=1}^l I_{i_0,i_0+j},
\end{align*}
$$

where $(2l + 1)$ is the length of the square side.
To determine the direction of the wood fibers need to estimate the relative contribution of periodicity in the x and y directions. For this purpose, the power of the $P_x$ and $P_y$ spectra should be calculated (figure 4d). Their rationing should be done [9]:

$$P_x = \sqrt{\sum_{i=0}^{k_{max}} w_{x,ik}^2}; \quad P_y = \sqrt{\sum_{i=0}^{k_{max}} w_{y,ij}^2}; \quad P_x^n = P_x / (P_x + P_y); \quad P_y^n = P_y / (P_x + P_y),$$

(4)

where $k_{max}$ is the upper limit of the analyzed interval of inverse distances (determined by the smallest possible distance between the annual layers); $P_{xn}$ and $P_{yn}$ are the normalized powers of the spectra.

Quantitative estimates of the periodicity of $P_{xn}$ and $P_{yn}$ allow us to determine the orientation angle of the fibers $\phi$:

$$\phi =\begin{cases} 90^0 P_{x}^n + 0^0 P_{y}^n, & P_{d1} < P_{d2}; \\ 90^0 P_{x}^n + 180^0 P_{y}^n, & P_{d1} > P_{d2}, \end{cases}$$

(5)

where $P_{d1}$ and $P_{d2}$ are the spectral powers in the diagonal directions (figure 4d).

Also, to remove uncertainty in the angle $\phi$ determining, it is necessary to investigate the diagonal directions $d_1$ (angle $45^\circ$) and $d_2$ (angle $-45^\circ$). The spectra of the intensity functions in the diagonal directions should be calculated. The power of these spectra should be calculated in the same way as above.

Milling was executed by the CNC machine PLRA4. The working area of this machine is $560 \times 380 \times 105 \ mm^3$. The maximum feed rate is $5000 \ mm/min$. Traveling positioning accuracy is $0.01 \ mm$. Repositioning accuracy is $0.05 \ mm$. This CNC machine specifications allow us to use it for experimental research. Pine, birch and oak wood were used in this research. The size of each workpiece is $500 \times 320 \times 30 \ mm$. A profilometer Hommel Tester T1000 was used to measure the treated surface roughness.

Analyzing of the simulation results and their comparison with the experimental data led to the following analytical dependence [9]:

$$v_{rate} = \frac{v_{rate}^0 + v_{rate}^{90}}{2} + \frac{v_{rate}^0 - v_{rate}^{90}}{2} \cos 2\phi,$$

(6)

where $v_{rate}$ is the feed rate of the cutter; $v_{rate}^0$ and $v_{rate}^{90}$ are the values of the optimal feed rate of the cutter in the directions along and across the fibers, respectively (experimentally determined for various types of wood); $\phi$ – the value of the orientation angle of the fibers.

3. Results and discussion

Using the optimal feed rates $v_{rate}^0$ and $v_{rate}^{90}$ (Table 1) in the formula (6) led to the following analytical dependences [9]:

- for the pine: $v_{rate}(\phi) = 1100 - 400 \cos 2\phi$;
- for the birch: $v_{rate}(\phi) = 1500 + 400 \cos 2\phi$;
- for the oak: $v_{rate}(\phi) = 1500 - 400 \cos 2\phi$.

(7) (8) (9)

These dependencies can be used in the milling machine control system for the adaptive wood milling. The angle $\phi$ between the direction of the milling tool and the wood fibers can be defined by the optical recognition method described above.

Figure 5 presents graphs of dependence $v_{rate}(\phi)$ for various types of wood (pine, birch, oak). These graphs show the difference between $v_{rate}(\phi)$ dependencies for several types of wood. For the oak and the pine, the feed rate $v_{rate}$ can increase if the angle $\phi$ increases. Vice versa, for the birch, it is necessary to decrease $v_{rate}$ if the angle $\phi$ increases. The implementation of the feed rate varying...
during milling allows us to raise equipment productivity and maintain the high quality of furniture workpieces processing.

\[ \text{Figure 5. Dependence between the cutter feed rate (} v_{\text{rate}} \text{) and the angle between the milling tool direction and the wood fibers (} \varphi \text{) for various types of wood: pine, birch, oak.} \]

The experimental results, where workpieces made of various types of wood (pine, birch, oak) are approximated using smooth curves (figure 6), show the dependence between the roughness \( R_m \) of the workpiece processed surface and the cutter feed rate \( v_{\text{rate}} \). Figure 6 shows an oak workpiece after milling operations across and along the fibers, performed with different feed rates of the cutter \( v_{\text{rate}} \): 900, 1300, 1700, 2100, and 2500 mm/min [9].

\[ \text{Figure 6. Dependence of workpiece surface roughness (} R_m \text{) on the cutter speed (} v_{\text{rate}} \text{) when milling across and along fibers of pine (} a \text{); of birch (} b \text{); of oak (} c \text{).} \]
The approximated dependence between the roughness \( R_m \) and the feed rate \( v_{rate} \) during milling along the wood fibers is presented by the line charts, marked with 1 (figures 6a, 6b и 6c). The line charts marked with number 2 show the approximated dependence between \( R_m \) and \( v_{rate} \) during milling across the wood fibers. Points, marked with numbers 3 and 4, represents experimental result values of this dependence.

The optimal range for the feed rate \( v_{rate} \) of cutters was found (table 1). Also, the optimal range for the rotation speed \( f_{cut} \) of cutters was found by the experiment [9]. They provide acceptable processing quality \((100 \leq R_m \leq 150 \ \mu m)\) and equals to 900 ... 1700 mm/min and 15000 ... 25000 rpm. These value ranges can be used in the software control of the adaptive milling of solid wood furniture workpieces.

| Type of wood | \( v^0_{rate}, \text{mm/min} \) | \( v^{90}_{rate}, \text{mm/min} \) | \( v^0_{rate} / v^{90}_{rate} \) |
|-------------|-----------------|-----------------|-----------------|
| Pine        | 900             | 1300            | 0.69            |
| Birch       | 1700            | 1300            | 1.31            |
| Oak         | 1300            | 1700            | 0.76            |

4. Conclusion

The proposed extended approach to the adaptive 3D wood milling involves adjusting control programs for a CNC machine. It is based on the information about the characteristics of each furniture workpiece. A preliminary stage is required to gather this information. In the first step, it includes non-contact ultrasonic scanning of the workpiece body. Next, the optical recognition of the wood fibers’ direction should be done in the local processing area of the workpiece surface. This area is mapped to the trajectory of the cutter.

The single methodical technique is applied in the developed structural schemes and algorithms in non-contact ultrasonic scanning and optical recognition. It consists of applying a virtual rectangular grid to the surface of the furniture workpiece. The cutter's trajectory is projected on this grid. Groups of grid cells, which contain fragments of the trajectory, are considered as local processing regions. These areas of furniture workpieces are interesting for the subsequent ultrasonic scanning and optical recognition. In other words, knowledge of these areas’ locations allows us to perform the ultrasonic scanning and optical recognition procedures described in the article selectively.

The applying of the extended approach to the adaptive 3D milling of the solid wood workpieces improves the quality of the obtained furniture parts and contributes to the satisfaction of the aesthetic needs of true furniture connoisseurs.

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