

TOWARD A PROCESS MONITORING AND CONTROL OF A CNC WOOD ROUTER: DEVELOPMENT OF AN ADAPTIVE CONTROL SYSTEM FOR ROUTING WHITE BIRCH

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Abstract. An adaptive optimization system for routing white birch was developed to control feed speed to produce a desired degree of surface roughness. The system consisted of an interconnected adaptive controller linked to a numerically controlled router. Online estimation of surface roughness was made based on directionalized measurement of sound pressure. By knowing the surface roughness at a given moment and its permissible limit, the adaptive controller was able to take decisive action to adjust the feed speed. The adaptive control system was able to detect changes in the surface quality and, as a result, vary the feed speed. Therefore, surface roughness was maintained below a predetermined level and productivity could be increased. Comparison with the resultant surface roughness when machining the same sample at constant feed speed confirmed the applicability of the adaptive control system for wood machining.

Keywords: White birch, routing, adaptive control system, cutting process, optimization, surface roughness prediction.

INTRODUCTION

The main objectives of process monitoring and control during machining are to optimize manufacturing speed and decrease production time. This optimization of machining conditions should not affect certain requirements for the quality of the final product. In wood machining, the control process should manage the major control variables such as feed or spindle speed and adjust them to approach optimum conditions for the chosen objectives such as machining time and/or surface quality. A current disadvantage of modern CNC systems is that machining parameters such as cutting speed and feed rate are preprogrammed offline. The machining parameters are usually chosen according to the experience of the programmer and/or from handbooks. To prevent failures, the machining settings are

typically conservative. Also, if the machining conditions (which may be uncontrollable such as grain angle) will change along the cutting path, cutting parameters are set according to the most problematic part of the workpiece. As a result, many CNC systems may operate under conditions that are far from optimal. Adaptive control systems provide continuous monitoring of a controlled process so that online adjustments of process variables can be made in real time.

The primary goal of wood machining is to obtain product with the desired shape, dimensions, and surface finish. It has been recognized that a number of factors influence surface roughness of a workpiece. Some of these cannot be controlled, eg properties of the material being cut or the machine and tool states (Sitkei and Magoss 2003; Gurau et al 2007). However, some factors such as machining conditions can be monitored and controlled. Feed and spindle speed have great influence on surface finish, and often a compromise

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must be made between desired surface roughness and machining speed (Lemaster et al 2000; Iskra and Hernández 2009).

Because of high feed speeds of cutting and harsh environmental conditions of machining (presence of vibrations, dust, and chips), in-process measurement of surface roughness is impracticable. Therefore, indirect phenomena such as acoustic emission (Cyra et al 1996; Cyra and Tanaka 2000) and vibration or sonic techniques (Iskra and Tanaka 2006; Denaud et al 2007) have been proposed as control parameters to evaluate surface roughness or the surface profile of wood during machining.

The main disadvantage of using contact measurements with accelerometers or acoustic emission sensors to monitor online processes is the need to place them as close as possible to the cutting zone to avoid a cross-transfer effect (Delio et al 1992). Conversely, signals acquired by noncontact sensors such as microphones can be disturbed if transducers are placed in a noisy environment, ie near other machines, and thus their application is restricted.

This study investigated a noncontact sound technique, insensitive to other noise sources, using a directionalized sound pressure signal measurement. An absorption/rejection tube padded with isolating foam was built around a microphone to limit the influence of unwanted noises. This construction together with an online module to assess surface roughness were used to build an adaptive optimization system to control feed speed to produce a desired surface roughness during routing white birch. Feed speed was chosen as the controllable parameter to assure a higher overall productivity with the spindle at its maximum rotation.

EXPERIMENTAL SETUP

Test Specimens

The specimens were made of white birch (*Betula papyrifera* Marsh.), which was chosen because the study was part of a larger research

program to promote value-added applications of undervalued wood species. Two flat-sawn boards were kiln-dried and stored in a conditioning chamber at 20°C and 40% RH, an 8% EMC. Five defect-free samples were cut from the boards, each having a specific grain orientation. The samples were then glued together forming two separate boards, 600-mm long, 200-mm wide, and 19-mm thick. The samples in the boards were oriented such that at the beginning of each board, the actual grain direction (in degrees) started at 90-45 and progressed through 90-88, 90-133, 90-0, and finishing at 90-71 (Fig 1). The cutting directions indicated as 90-0 and 90-45 implied cutting along the grain, 90-88 nearly perpendicular to the grain, and 90-133 against the grain. One of the glued boards was used for the tuning procedure, whereas the other was machined to study the performance of the adaptive controller.

Cutting Conditions

The experiments were carried out on a Fulltech Centek 5121-A, 3-axis CNC machine equipped with a 10/110 Osai controller. Up-milling along a straight path was performed with a 30-mm-dia cutter having two tungsten carbide (K-10) straight-insert knives with rake and clearance angles of 20° and 15°, respectively. The rotational speed of the spindle was kept at 24,000 rpm. Edge jointing was performed with a 19-mm cutting width (thickness of samples) and 1- to 3-mm depths of cut.

Sensor and Data Acquisition

A free-field ICP microphone (PCB model 130D20) was used to monitor the cutting process. The microphone was positioned at 400 mm, directly toward the cutting zone (Fig 1). The measurement of sound pressure level by a single microphone is scalar and therefore will equally detect acoustic signals from all directions unless some directionalization technique is used such as an absorption/rejection method (Delio et al 1992). In this method, the microphone is surrounded by absorptive materials that isolate unwanted sounds that are alien to the process.

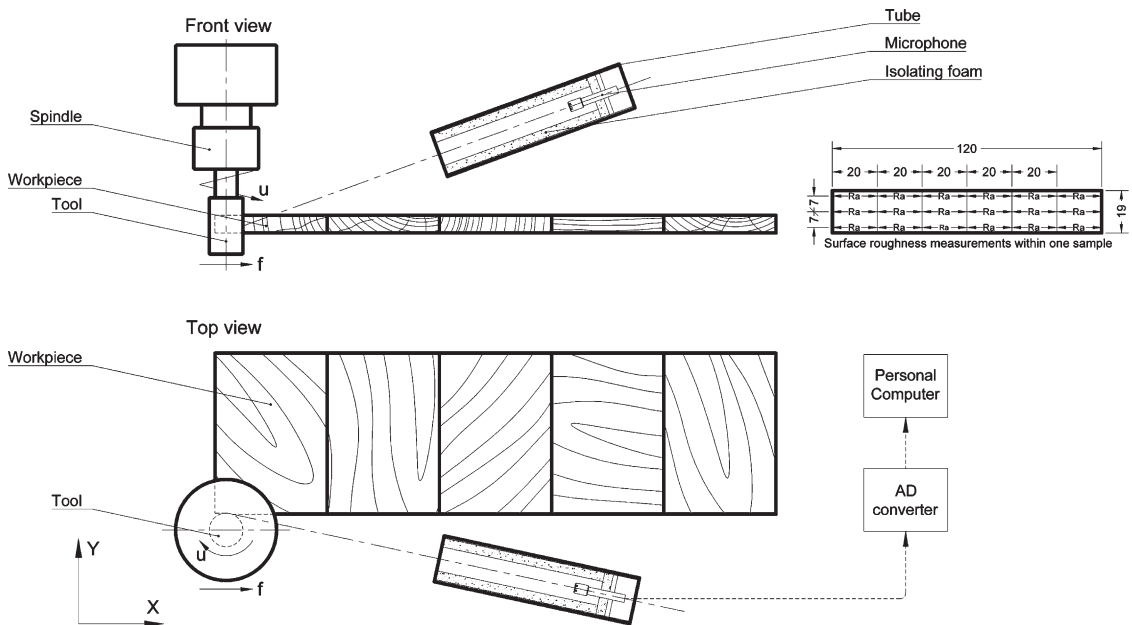


Figure 1. Experimental setup with data acquisition system. Notes: u = rotational speed; f = feed speed, R_a = surface roughness measurement locations (dimensions in millimeters).

Therefore, a special tube padded with isolating foam was prepared. The microphone was placed inside the tube, which was attached to the spindle to always have the microphone at a constant distance from the cutting zone. Since the ICP transducer was used, no additional preamplifier was required. A dynamic signal analyzer (National Instruments, PCI-4474) acquired the signals at a frequency of 51.2 kHz. Task software was developed using LabVIEW programming to acquire and process the data.

Surface Roughness Measurement

After each cut, the roughness of the machined surfaces was measured using a Hommel Tester T1000 profilometer equipped with an inductive pick-up diamond stylus tip with a 5- μ m radius and a cone of 90°. A Gaussian filter with a 2.5-mm cutoff wavelength was used to process the data. The measurements were conducted following the feed direction, across the knife marks, with a 1-mm/s traverse speed. Previous studies (Iskra and Hernández 2009) showed that the arithmetic

average of the absolute deviations from the mean surface level, the R_a parameter, adequately described the machined surface of samples having different grain angles. Surface roughness measurements were performed over the entire length of the board after each cut. Each measurement was carried out over a 20-mm fixed evaluation length (Fig 1). Three parallel measurements were performed over the board thickness, which were averaged for an estimate of the surface roughness.

Adaptive Controller

The aim of this study was to develop an adaptive control system that would adjust the feed speed of the CNC router based on surface roughness assessment. Surface roughness was estimated online based on the sound pressure signal and the actual feed speed that was determined previously (Iskra and Hernández 2009). The adaptive Proportional Integral Derivative (PID) controller was developed using a standard PC and the LabVIEW programming environment. A block

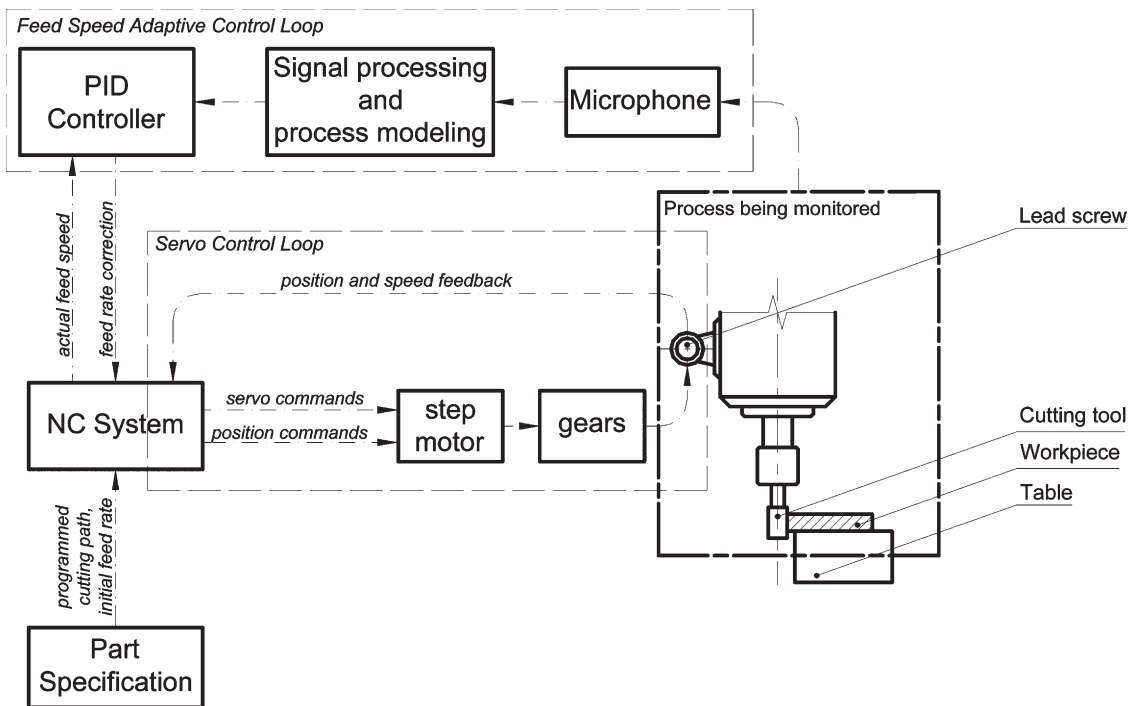


Figure 2. Adaptive control optimization loop integrated into pre-existing CNC control system.

diagram of the CNC control system and the feed speed control loop is shown in Fig 2. During a machining operation, programmed input data (dimensional coordinates, tool compensation, rotational speed, and initial feed speed) were applied to the CNC controller, converted into servo command signals, and executed. In addition, an adaptive loop was added to override the initial feed speed according to the desired and evaluated surface roughness. The task software developed was responsible for collecting, conditioning, and processing data; estimating surface roughness; choosing the appropriate feed speed; and communicating with the CNC machine. A connection between the PC and the NC system was made using an Ethernet network, a cndex server, and a mini Direct Numerical Control protocol (Osai 1998, 2001). This connection was used to transmit the feed speed override from the PC to the CNC system and to receive the actual feed speed from the CNC. The actual feed speed was used by an implemented neural

network to evaluate surface roughness (Iskra and Hernández 2010).

Proportional Integral Derivative Control Strategy

A controller is a component of a system that permits a process to operate within programmed limits. The controller used in the study was based on PID theory. A PID controller is a standard feedback loop component in industrial control applications. It compares a tasked setpoint with the process variable at a given moment to obtain the error. The setpoint is a chosen value toward which the controller aims its output. Based on the sign and magnitude of the error, the controller calculates an appropriate controller action. The PID controller output is the summation of the proportional (P), integral (I), and derivative (D) actions (LabVIEW 2009):

$$u(k) = u_P(k) + u_I(k) + u_D(k) \quad (1)$$

that practically can be denoted as:

$$u(t) = K_C \left[(SP - PV_f) + \frac{1}{T_I} \int_0^t (SP - PV_f) dt - T_D \frac{dPV_f}{dt} \right] \quad (2)$$

where K_C is the controller gain, SP the setpoint, PV_f the process variable at a particular moment, and T_I and T_D are the integral and derivative times, respectively.

The actual controller output was limited to the range specified for control output:

$$\begin{cases} \text{if } u(k) \geq u_{max}, & \text{then } u(k) = u_{max} \\ \text{if } u(k) \leq u_{min}, & \text{then } u(k) = u_{min} \end{cases} \quad (3)$$

where u_{max} and u_{min} are the upper and lower limits of the controller output, respectively. In the controller, the output was forced within the range specified by u_{max} and u_{min} , which correspond to the appropriate maximum and minimum feed speeds chosen by the operator.

Controller Tuning

Each controller must be appropriately tuned before applying it to a process. Controller gain and integral and derivative times have to be correctly chosen to ensure proper action of the controller. The controller designed in the study was initially pretuned using the Ziegler and Nichols theory of quarter-decay-ratio tuning techniques. This criterion is derived from a combination of theory and empirical findings (LabVIEW 2009). After initial tuning, each controller was manually adjusted based on performance obtained from a number of trial and error tests. This tuning was necessary since the ultimate gain-tuning procedure requires putting the process into steady-state oscillation and then slowly increasing the proportional gain. For wood machining, it was not possible to establish a steady-state oscillation since the cutting process is intermittent, limited by the machined element length. Also, the cutting process includes at least three phases, and two, tool approach and retraction, are not associated with actual cutting.

Moreover, the time required to machine the prepared board was too short to manually increase the parameters.

RESULTS AND DISCUSSION

Setpoint and Gain Scheduling

To control a process, a desired value of the parameter under control (setpoint) must be chosen. In our case, the controlled parameter was the surface roughness evaluated online by task software (Iskra and Hernández 2010). The desired value was chosen arbitrarily based on previous findings of the surface quality of routed white birch wood (Iskra and Hernández 2009). In that experiment, surface roughness was determined for white birch samples of six different grain orientations (0, 45, 90, 120, 135, and 150°), routed at five feed speeds (1-20 m/min), and for three depths of cut (1-3 mm). At the same time, the surfaces were visually evaluated to recognize torn grain, which was assigned with binary values of 1 or 0. After analysis of 270 cases, it was determined that torn grain appeared on surfaces of 11 μm and higher R_a (Fig 3). Therefore, to avoid torn grain, $R_a = 11$ was chosen as the initial setpoint. However, we must remember that the surface roughness measurement is burdened with error. The root mean square error of the model used to predict surface roughness was $R_a = 3.0 \mu\text{m}$ (Iskra and Hernández 2010). Therefore, by choosing the setpoint of $R_a = 11 \mu\text{m}$, we could generally expect values of surface roughness of $R_a = 8-14 \mu\text{m}$. Given that an R_a value greater than 11 μm is an indication of a damaged surface, values lower than that are qualitatively excellent. Therefore, to avoid torn grain from the model approximation error, a setpoint of $R_a = 8 \mu\text{m}$ was selected for the controller.

The PID parameters (K_C , T_I , T_D) chosen during the tuning procedure may not always be optimal if the dynamics of the controlled process change with operating conditions. In the experiment, the dynamics changed abruptly whenever a sample with a different grain angle was cut. Therefore, gain scheduling, ie a system where the controller

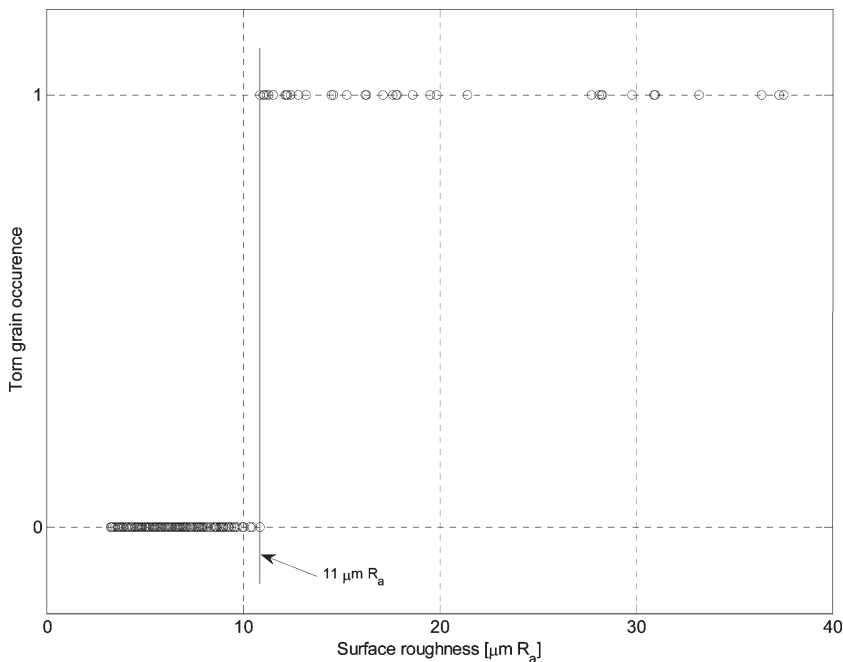


Figure 3. Relationship between the presence of visually evaluated torn grain and the surface roughness measured. Number of samples: 270; “0” means no torn grain occurrence, “1” indicates the presence of the torn grain.

parameters change based on measured operating conditions, was applied. Gain scheduling was based on the actual process variable value and its distance from the chosen setpoint. When there is a significant gap between the actual process variable and the setpoint, more radical action is required to adjust the controlled parameter. In contrast, when the process variable is near the chosen setpoint, it requires only subtle change of the controlled parameter for fine tuning. In this study, three sets of PID parameters were applied to assure proper action over a wide dynamic range of the process variable. When the process variable was in the range of $\pm 2.5 \mu\text{m } R_a$ of the setpoint ($R_a = 5.5\text{--}10.5 \mu\text{m}$), the controller was set to have a fairly mild response, which is indicated by low proportional gain (Fig 4). When the gap between the process variable and the setpoint is greater than $\pm 2.5 \mu\text{m } R_a$, the controller response was set to have a faster response (higher K_C). When the process variable was lower than $2.5 \mu\text{m } R_a$ of the setpoint, the integral time was lowered to avoid overshooting the setpoint. The PID

parameters had to be chosen carefully. A too rapid controller response could cause the system to oscillate, which can lead to destruction of the workpiece and eventually the machine tool. The dynamic stiffness of the CNC machine tool-spindle support system may also be an issue for proper PID parameter selection. Abrupt changes (decreasing) of the feed speed during machining results in detectable waviness left on the surface caused by a sudden increase of cutting forces and momentarily reduction of the system stiffness. Therefore, the PID parameters should be chosen carefully taking into account the dynamic stiffness of the machine tool, which can be different for each CNC machine.

Controller Performance

The performance of the controller was tested using a custom-made board consisting of five wood samples glued together, each one with a different grain orientation. Allowable maximum and minimum feed speed was set to be 18 and 5.25 m/min, respectively. These values were

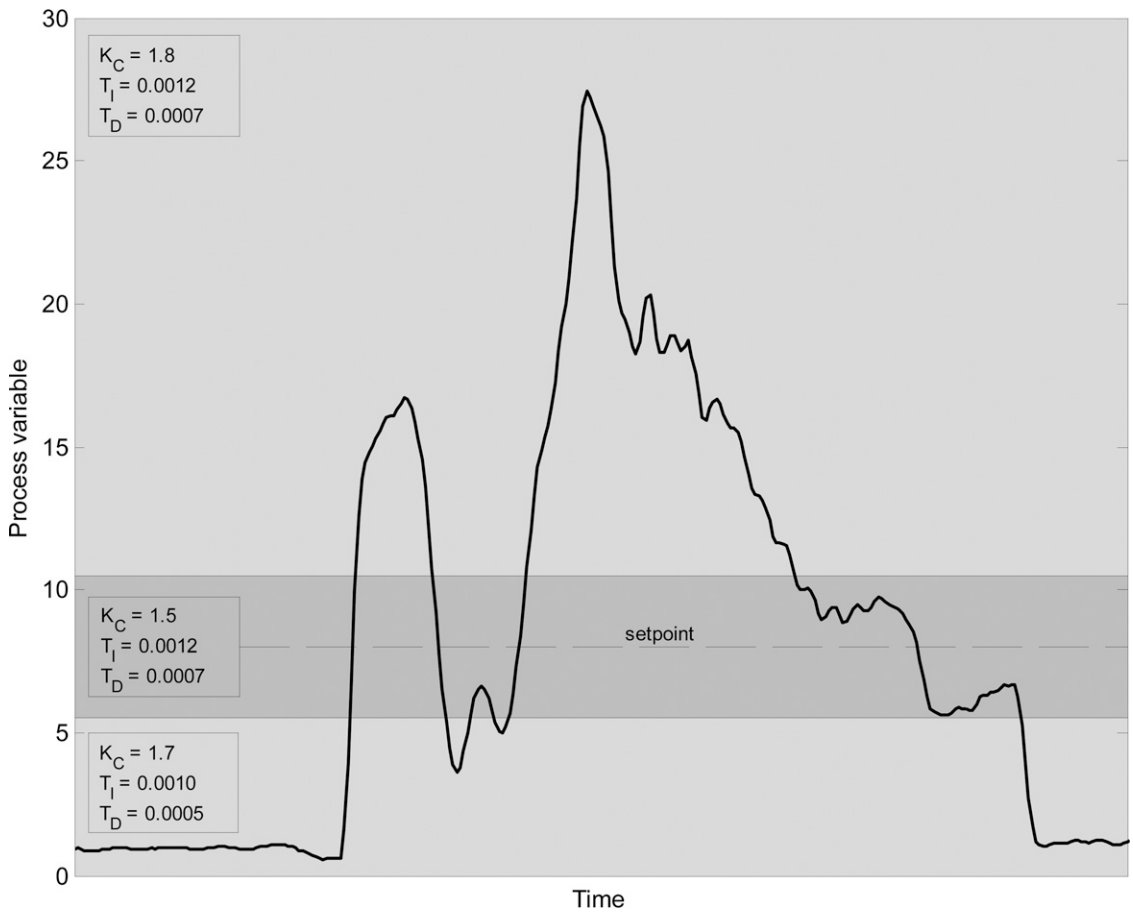


Figure 4. Gain scheduling used in the adaptive optimization system. Different controller response is obtained using different Proportional Integral Derivative (PID) parameters in chosen operational areas. Process variable means the estimated surface roughness. Different shadings indicate areas with different PID parameters.

calculated as a percentage override (120 and 35%) of the initial feed speed (15 m/min) of the executed program stored in CNC memory. Previous experiments (Iskra and Hernández 2009) revealed that machining white birch wood across the grain with 5.25 m/min feed speed should not produce a surface rougher than $R_a = 11 \mu\text{m}$. Since the spindle should be permitted to reach its maximum feed speed from null before it engages in cutting, a certain distance should be allowed between the initial tool position and beginning of the workpiece. Taking into consideration the acceleration capability of the spindle support, a distance of 50 mm for tool entrance and 50 mm for tool exit was established.

An example of the adaptive control system performance while routing at 3-mm depth of cut is shown in Fig 5. Initially, the spindle reached its maximum rotational speed of 24,000 rpm and allowable feed speed of 18 m/min. With these cutting parameters, the tool approached the workpiece and machining occurred at the point of 0 mm. The x-axis of Fig 5 is scaled in the terms of the workpiece length and shows consecutive wood samples. Before the tool engagement (tool approach, no cutting), it is shown that the system evaluated the actual surface roughness near $R_a = 0 \mu\text{m}$. This is an obvious simplification because even very slow feed-speed machining would not produce such a smooth

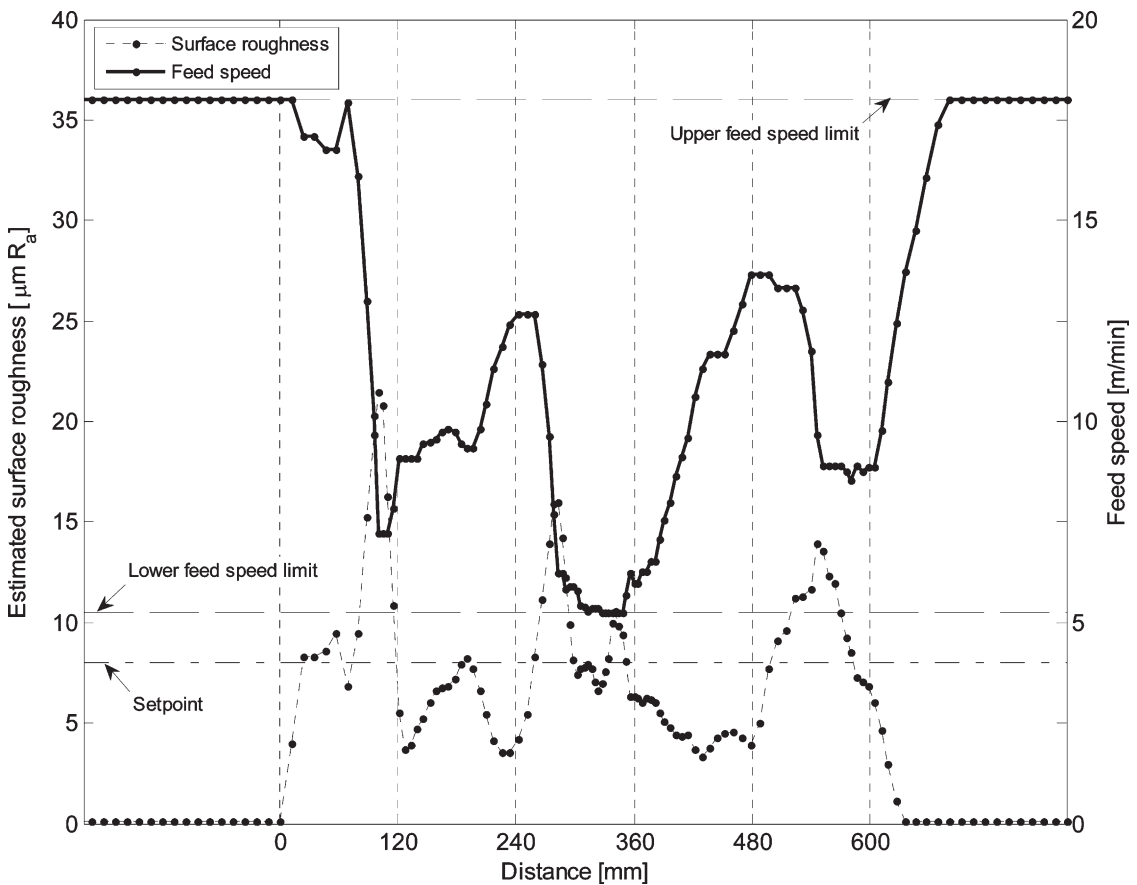


Figure 5. Performance of the adaptive control optimization system. The x-axis (distance) indicates the position of the tool along the workpiece.

surface because of the anatomical structure of wood. However, the mathematical model of the surface roughness evaluation assumed close to zero surface roughness when the spindle was running idle and the tool was not yet cutting. The actual cutting occurred immediately after the 0-mm mark denoting the beginning of the workpiece. At this stage, the feed speed was still at the maximum allowable level, because the adaptive controller must gather data, process it, and produce an appropriate response and therefore the reaction is always one step behind the actual cutting state. The loop was programmed to do a complete gathering of data and produce an output every 40 ms. As the evaluated surface roughness rose above zero and before it reached the established setpoint, the feed speed had been

adjusted and decreased locally to 17 m/min. When the process variable (surface roughness) approached the setpoint ($R_a = 8 \mu\text{m}$), changes in the feed speed were minor because of the conservative PID parameters chosen for this region (Fig 4). If the surface roughness increases substantially beyond the setpoint, the feed speed will drop immediately at a high rate permitted by a different set of PID parameters. However, this drop must not be so radical as to cause overshooting, resulting in oscillation of the feed speed that can damage the workpiece, tool, and machine. As the cutting progressed, the tool engaged the second wood sample (between 120 and 240 mm). Since the feed speed was already much lower than the initial 18 m/min and the evaluation module assessed the surface roughness to be below the

allowable limit, the decision was to increase the feed speed.

When a tool engages in a new wood sample of a particular grain angle, it may appear that the ideal performance should be for the system to quickly establish the ideal feed speed and keep the feed speed more or less constant during machining the workpiece. One must understand that this process is dynamic, and changing the feed speed in one step results in a dynamic change of the signal, which affects the evaluation in the next step. Moreover, the CNC control system is burdened with a time delay, therefore adjustments of feed speed commanded by the controller are not executed immediately. This delay is caused by certain time responses of signals produced and transferred to the servo and also by the reaction of the motors, which have to drive heavy supports with the electrospindles mounted on them. Furthermore, to avoid abrupt alterations of the output variable (feed speed), the process variable (surface roughness) was passed through a fifth-order low-pass finite impulse response filter, which slowed the response of the adaptive controller. The effect is most visible at the end of cutting (immediately after 600 mm in Fig 5), where the cutting had definitely finished but the evaluated surface roughness diminished, slowly reaching the zero level 0.2 s after the machining was completed. The low-pass filter may also negatively influence the surface roughness estimation, however preliminary tests showed that it was required to smooth the performance and avoid oscillation.

The third consecutive wood sample (240-360 mm) had a grain orientation of 133° , thus the cutting was against the grain and the surface roughness produced was the highest (Iskra and Hernández 2009). The controller, after 80 ms of delay, slowed the feed speed, eventually reaching the lower limit of 5.25 m/min. The fourth wood sample (360-480 mm) had the grain orientation parallel to the feed speed vector, therefore the surface roughness was kept below the setpoint, although the feed speed rose almost throughout the entire machining path. In this case, it would be preferable for the feed speed to accelerate

faster, because the surface roughness was substantially below the setpoint. However, a faster response could cause excess overshoot of the process variable over the setpoint, and to compensate, the controller would produce an opposite reaction, which would lead to undesirable and hazardous oscillation. The final wood sample (480-600 mm) had a 71° grain orientation. When the tool engaged this sample, the adaptive controller caused the feed speed to slow; initially, the decrease was sluggish, but when the surface roughness continued to increase, the controller reaction was more decisive. After completing machining of the board, the estimated roughness decreased gradually and the feed speed increased, reaching the upper feed speed limit in 0.3 s.

The progress of the adaptive controller differed slightly each time the machining was performed using the same cutting conditions and controller PID parameters. Machining samples of different grain orientation with variable feed speed is encumbered with high dynamic unpredictability (additional sources of vibrations) affecting the surface roughness prediction. This unpredictability adds to the overall error because the prediction model was created from data obtained while machining at constant feed speed.

To test the reliability of the adaptive controller, the workpiece was machined three times using the same cutting and PID conditions. These tests were for two depths of cut, 1 and 3 mm, to ensure performance of the surface roughness evaluation module developed previously (Iskra and Hernández 2010). The module used the actual feed speed and the frequency spectrum of the sound pressure signal to instantly evaluate surface roughness during machining. The same model was used to evaluate surface roughness regardless of the grain orientation and depth of cut. As the depth of cut increases, surface roughness remains constant (Iskra and Hernández 2009), but the sound produced by the cutting tool is altered. The same surface roughness prediction model for a given range of depths of cut should be considered a method to estimate surface roughness rather than providing a precise

measurement. Since the performance of the adaptive controller varied slightly, three cuts were performed and the resultant cutting time and the maximum and average surface roughness were measured and presented as an average (Table 1). The results differed depending on the cutting depth; cutting time increased (and therefore the average feed speed decreased) by 8% when the depth of cut went from 1 to 3 mm. The difference is accounted for in the error of the surface roughness evaluation module. Slight underestimation of surface roughness may cause the controller to use higher feed speeds. Conversely, slight overestimation of the surface roughness may cause the controller to set the feed speed slower than optimal.

Since the workpiece consisted of five samples of different grain orientations, the surface roughness was expected to vary as the cutting was made with and against the grain. The most critical wood sample was with a 133° grain angle cutting against the grain. Previously, it was found that this cutting orientation is very unfavorable (Iskra and Hernández 2009). The average surface roughness measured after cutting with the use of adaptive controllers was less than $R_a = 8 \mu\text{m}$ for both 1- and 3-mm depths of cut (Table 1). However, the maximum surface roughness detected surpassed the optimal ($R_a = 11 \mu\text{m}$) setpoint and reached $R_a = 18.6$ and $12.1 \mu\text{m}$ for 1- and 3-mm depths of cut, respectively. Closer investigation of the surface roughness showed that the roughness reached and surpassed the $R_a = 11 \mu\text{m}$ setpoint only when machining the 133° sample (against the grain) (Figs 6 and 7). When routing with a 1-mm depth of cut, the controller permitted a greater feed speed when machining the 88° sample. As soon

as the tool engaged the 133° sample at this feed speed, a rough surface was produced at the beginning of the cut. After a short period of time, caused by the delays explained previously, the surface roughness dropped below the chosen setpoint (Fig 6). After the initial phase required for the controller to react, the surface roughness was kept in the proximity of the setpoint. Machining at a greater depth of cut (3 mm) caused the controller to behave more conservatively by choosing a slower feed speed when machining the 88° sample (Fig 7). Slower feed speed at this stage did not produce greater surface roughness when the tool engaged in the 133° sample (Fig 7). The first section (20 mm) of the workpiece had a roughness of $R_a = 12.1 \mu\text{m}$, which then decreased and was kept in the proximity of $R_a = 11 \mu\text{m}$. The adaptive controller does not differentiate between the terms “below” and “above.” The principle is to keep the outcome as close to the setpoint as possible irrespective of the sign of the error (“below” or “above”).

To compare the performance of the adaptive controller, the same workpiece was machined using a constant feed speed, which was based on the average feed speed measured during the three trials of routing with the use of the adaptive controller. In this case, the average feed speed and time of machining were equal, which permitted comparisons of surface roughness with and without the adaptive controller. It should be stated that the average feed speed was calculated from the moment the tool engaged and until it left the workpiece. The full machining cycle requires the tool to travel a longer distance than the length of the workpiece allowing a certain distance for the tool entry and exit. In that case, the adaptive controller would be advantageous

Table 1. Performance of the adaptive control optimization system when routing the test board at different depths of cut.

Depth of cut (mm)	1	3
Cutting time (s)	3.37 (0.27) ^a	3.64 (0.33)
Average feed speed (m/min)	10.75 (0.82)	9.97 (0.88)
Average feed speed including the tool entrance and exit (m/min)	11.19 (0.85)	10.32 (0.92)
Average surface roughness measured ($\mu\text{m } R_a$)	7.95 [11.41] ^b	7.69 [10.15]
Maximum surface roughness measured ($\mu\text{m } R_a$)	18.55 [35.54]	12.12 [29.98]

^a Standard deviation in parentheses.

^b Data for cutting at corresponding constant feed speed in brackets.

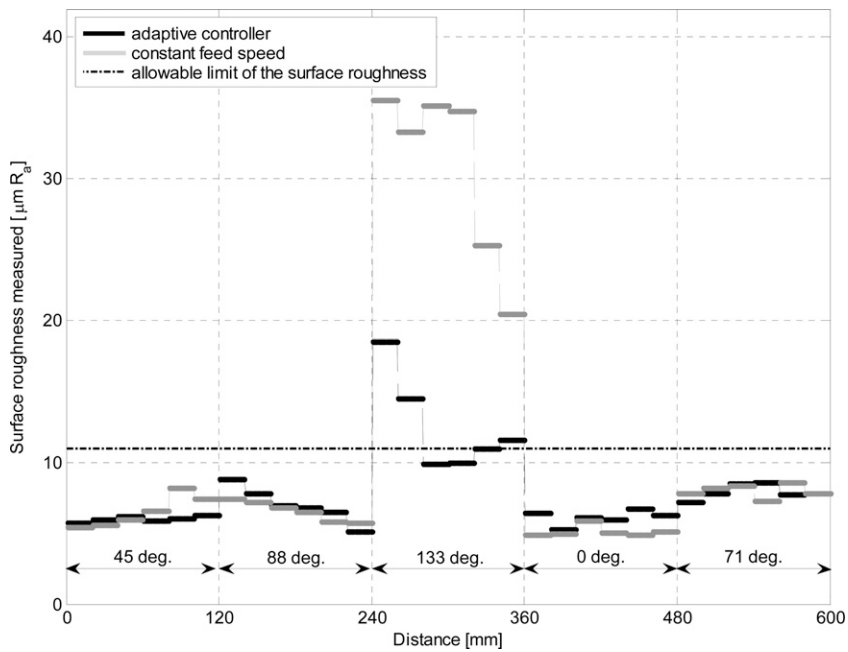


Figure 6. Surface roughness with and without the use of adaptive control optimization when routing at 1 mm of depth of cut. The x-axis (distance) indicates the position of the tool along the workpiece.

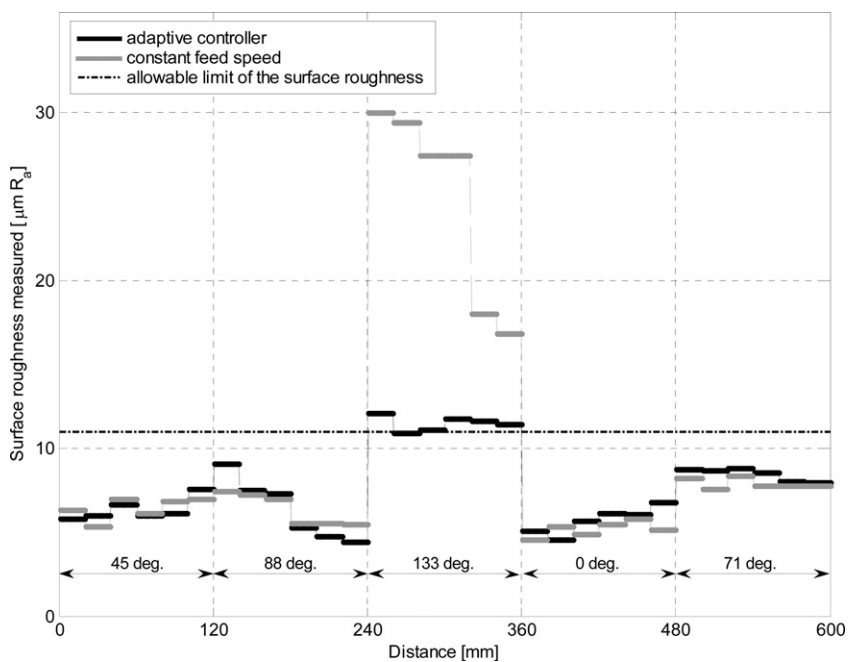


Figure 7. Surface roughness with and without the use of adaptive control optimization when routing at 3 mm of depth of cut. The x-axis (distance) indicates the position of the tool along the workpiece.

since the initial feed speed was higher than the average value (Table 1). Despite that, we decided to use the average feed speed excluding the distances for entry and exit because for much longer workpieces, the difference would not be appreciable. The comparison of the surface roughness produced with and without the use of the adaptive controller showed that there is not much difference between the results while machining workpieces of 45, 88, 0, and 71°. The real difference can be noticed when machining the 133° sample (against the grain). The adaptive controller recognized the poor quality of the surface and adjusted the feed speed, obtaining an average surface roughness more than twice as smooth (59 and 54%) as machining with constant feed speed. The much higher surface roughness at the first 80 mm of the 133° sample was from red heartwood. Machining heartwood at this angle produces much greater roughness than sapwood. Moreover, the presence of heartwood in the 45, 88, and 71° samples did not produce significantly higher surface roughness. This effect may be attributed to the lower cohesion of fibers from biotic effects such as fungi or bacteria in the heartwood of white birch. However, for the purpose of comparison between the roughness obtained with and without the use of an adaptive controller, the presence of heartwood can be neglected since the same workpiece was used in both cases.

CONCLUSIONS

The performance of the adaptive control system based on surface roughness prediction modeling was examined in a routing application. Results showed that the adaptive controller was able to evaluate the surface roughness of white birch and adjust the feed speed to maintain the surface roughness at or below a predefined level. The gain scheduling adjusted the PID parameters in accordance with the actual error between the process variable and the setpoint, permitting swift reaction when the error was large and fine-tuning for minor error. The controller tuned the feed speed based on the online surface roughness prediction model such that the upper

allowable surface roughness was limited and the feed speed was increased whenever possible. The operational time delay resulting from computation, data transfer, and mechanical devices influenced the performance, especially when the grain orientation rapidly changed to the most unfavorable at 133°. After a short period to compensate for the time delay, the feed speed was adjusted and the resultant surface roughness dropped to the required level. Also, the depth of cut slightly influenced the performance since the same surface roughness evaluation model was used for 1- to 3-mm depths of cut. The comparison between the resultant surface roughness obtained using the adaptive controller and that using a constant feed speed demonstrated the advantages of the former. The resultant surface roughness of the most sensitive (133°) sample was reduced over 50% when using the adaptive control system.

A larger program including a greater number of samples, wood species, and cutting conditions should be conducted to demonstrate the usefulness of this method. The influence of the tool wear on surface roughness prediction should be also investigated.

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