Laser cutting technology in wood and furniture conservation

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Abstract

Laser cutting is a promising technology for wood and furniture conservation because it combines high speed with great precision and allows for simple reproducibility. Still, systematic examinations in this area of application are rare. This paper considers prospects and limitations of the technology as well as aspects regarding the ethics of conservation. An experimental part examines different lasers for cutting veneers of varying thickness, optimizes their parameters and offers practical advice for the reconstruction process. A survey on four conservation-restoration projects utilizing Laser cutting technology broadens the perspective to allow more generalized conclusions. Laser cutting technology is especially useful for repetitive tasks that require a high level of accuracy. In comparison to hand cutting, the use of lasers requires a longer preparation time before reaching desired results. Other practical key challenges are the effective, error-free and efficient digital conversion of the pattern as well as the compensation for non-orthogonal or darkened (charred) cutting edges. Results of this study and survey indicate that each laser has individual strengths and weaknesses and that a universal laser for cutting wood does not exist. Selecting the appropriate laser and beam parameters is crucial for success and depends, amongst other things, on the material, its thickness and the shape to be cut.

Introduction

Cutting with light might seem a little odd at first. A focused laser beam is, however, one of the highest power density sources. Laser cutting became the most frequently used industrial application of the laser, due to its cutting speed and high-quality cut. Even artisans and architects have utilized this technology for their artworks and architecture models for a long time.

In the field of conservation, lasers are known for cleaning surfaces and removing layers of unwanted paint (or coatings in general), as well as for documentation, diagnosis and analysis. Comparably less attention has been paid to utilizing lasers for cutting marquetry and inlays in wood and furniture conservation, with only few systematic studies.[1] Hence, the aim of this paper is to introduce this subject in an accessible manner and to transmit basic principles of the Laser cutting technology in the field of wood conservation and restoration. After presenting the technical basics of laser cutting, exemplary digitalizing of a typical marquetry ornament shows how the vector file used by the laser device is created and prepared. Apart from summarizing practical challenges of the comparably time-consuming digitalization process, alternative approaches to the task are briefly discussed. Using the self-prepared vector file, experiments at Fraunhofer Institute for Material and Beam Technology Dresden employ three different lasers to cut the ornament shape as well as test pieces in maple and walnut wood veneer of varying thickness. After determining suitable laser parameters, the laser-cut workpieces are compared among each other and against hand-cut results in several aspects of production quality: quality of cut edges, kerf width and size/repetition accuracy. In order to broaden the scope and allow more generalized conclusions, a survey on four conservation projects illustrates suitable applications of the technology as well as the users' motives and experiences. Ethical aspects to this innovative technology in the context of the conservation ethical guidelines are considered before drawing conclusions.

The compilation and exchange of practical examples of work with lasers, as provided here, may support exploring and exploiting the potential of this technology in the field of wood and furniture conservation.

Technical basics

To support the interpretation of results and arguments throughout the paper, this section briefly summarizes technical basics of Laser cutting technology. It also explains selected processing parameters and how they can affect the cutting process.

The physics of laser light

Light is electromagnetic radiation and is carried by electromagnetic waves. A wave has a trough and a crest. The horizontal distance between two consecutive troughs (or crests) is the wavelength (λ), customarily measured in nm or µm. Frequency (v) is the number of waves passing a given point per time, customarily measured as number per second in hertz (Hz). It is inversely related to the wavelength via the speed of light, so that electromagnetic radiation with higher frequencies has shorter wavelengths. Radiation with shorter wavelengths (that is higher frequency), for example ultraviolet light, carries relatively more energy per photon than radiation with longer wavelengths (that is lower frequency), for example infrared light. Visible light has its spectrum between 0.390 and 0.700 µm.

Ordinary and laser light differ, because ordinary light consists of electromagnetic radiation with different wavelengths produced by spontaneous emission. In contrast, laser light is based on the principle of 'light amplification by stimulated emission of radiation'. It is monochromatic, unidirectional and coherent, meaning that all its light waves have the same wavelength, the same direction, and are in phase with each other. Due to these characteristics it is possible to project a laser beam over great distances at low divergence, for example using it as a laser pointer. Focusing the beam to a very small focal spot diameter (spot size) increases energy density to very high levels. The minimum spot size is proportional to the wavelength and general design characteristics of the respective laser machine.[2]

Laser types

Lasers are usually classified along their active medium, which is the source of the amplification within a laser. The active medium can be gaseous, as with carbon dioxide (thus CO_2 laser, λ=10.6 µm) or solid state, for example neodymium-dotted yttrium aluminum garnet crystal (Nd:YAG laser, λ=1.064 µm). Both lasers are amongst the most widely used industrial lasers for macro-applications. In addition, there are frequency-multiplied lasers, which have even shorter wavelengths, for example the frequency-tripled Nd:YAG laser with λ=0.355 µm. Because of the shorter wavelength the frequency-multiplied laser can theoretically achieve a smaller focused spot size.[3]

The wood-cutting process

Like most mechanical cutting devices, a Laser cutting machine is typically computer numerically controlled (CNC). The laser generates a high-intensity laser beam that is controlled and guided by shutter control and beam guidance train, which can be mirrors (CO_2 laser) or flexible fiber optic cable (Nd:YAG laser). Then, the focusing optics of the laser head use lenses to focus the laser beam onto the workpiece surface. The wood absorbs the focused, high-energy radiation at the focal point, rapidly heats up and locally pyrolyzes and vaporizes in the cut line. Because the thermal reaction is a self-limiting process, there is just a narrow heat affected zone (HAZ) along the cut line. Due to the high temperatures at the cut zone, the cut edges of wood are usually darkened and charred. An assist gas can support the cutting process (see below).[4]

Laser parameters affecting the quality of cut edges

Wavelength (λ) of the laser radiation: the wavelength of the laser determines whether the radiation is absorbed, transmitted or reflected by the material to be cut. A higher absorption rate of the material favors the cutting process. The wavelength with the highest absorption rate varies (greatly) between different materials.

Operating mode and laser pulse repetition frequency

Lasers in continuous-wave (cw) operation mode emit a continuous beam. In pulsed-wave (pw) mode the laser beam appears in short pulses at the pulse repetition frequency (in hertz, Hz), which varies greatly between different lasers and/or applications. One of the advantages of the pulsed-wave mode is the variable and precisely controllable output power.

Laser power: Average output power of the laser in Watt (W): The higher the laser power the higher the energy input to the cutting zone. Note that the average laser power in pw mode varies also along the laser pulse repetition frequency.

Cutting speed: The cutting or process speed describes the movement of the laser head/laser beam. Changing the cutting speed will alter the energy input to the cut zone. That is, the faster the cutting speed, the less time to absorb the laser radiation and the less time for heat propagation in the material, which will result in a narrow cut kerf and HAZ. Cutting too slowly will result in a higher heat input, more material vaporization and burning processes.

Single- or multi-pass process: The laser can cut out programmed shapes in one run or by multi-pass processing, so the material is removed layer wise. This means the laser beam follows the cut line a specific number of times and allows cutting with less power.

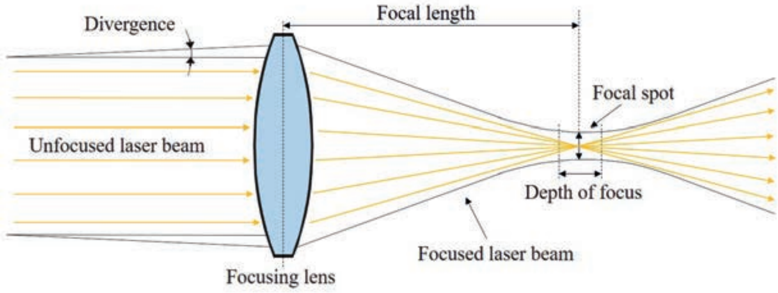

Figure 1 Schematic diagram of a focused laser beam.

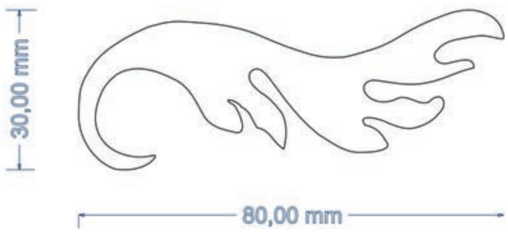

Figure 2 Vectorized ornament.

Focal spot/point: The area in which the focused laser beam has the smallest diameter and highest power intensity (figure 1). Because the focal spot may not be limited to one point, the length of the zone with almost the same diameter of the laser beam is called the depth of focus. Its length varies along the geometry of the focused beam. The focal point position describes the position of the focal spot in the material.

Focal length (f): Distance between the focusing optics and the point of the smallest beam diameter (figure 1). The focal length is determined by the lens of the Laser cutting device. The working distance is the distance between the focusing optics and the workpiece surface.

Assist gas: Pressurized gas can support the cutting operation by removing vaporized debris from the cut zone, regulating and controlling excessive burning and protecting the optics from particulates. A coaxial jet flow ejects the assist gas in the same direction as the laser beam through the nozzle of the laser head. A cross-jet with lateral ejection of compressed gas mainly protects the optics. Different gas pressures and types of assist gases can be employed, for example air/oxygen to support pyrolysis or nitrogen to limit pyrolysis.

Material properties: Besides the laser parameters the influence of material properties is crucial for the cutting process. The absorption rate of the laser radiation determines the energy input or rather the efficiency of the Laser cutting process. The thermal properties of the material are another major aspect. For example, wood has a low thermal conductivity and its specific heat capacity is three times higher than that of iron. At approximately 100 °C the pyrolysis begins, the flashpoint is about 230 °C[5] Other important factors affecting the cutting process are material composition, thickness, density and moisture. By varying the featured parameters the laser can cut different materials of varying thickness without direct contact, it operates self-limiting and can be well controlled in its intensity.[6]

Preparing the digital blueprint

Before shapes can be cut out of the material, they must be defined in a CNC-processable vector format, like AutoCAD or DXF. The vectors of the shapes will be converted to cut paths by the Laser cutting device's software. The advantage of a vector file over a bitmap with raster dots is that vector graphics are already path based and fully scalable images.

There are different possibilities to convert, that is digitalize, an actual ornament or complementary piece of veneer into a vector file. In my experiments the following rather manual procedure was most successfully employed to come up with the vector file.

A decorative ornament of a bureau from the eighteenth century with a complex curved shape was selected. The outline was copied onto white paper with a black fineliner pen (a small tip size of about 0.1 mm is crucial). Afterwards, the drawing was scanned with a flatbed scanner in high quality together with a scale, which is essential for the further process. The resulting JPEG file was converted into single-lined vector paths via the Centerline Trace feature of the vector graphics editor CorelDraw (figure 2). With this feature, the software avoids creating double lines around the limits of the (single) pen lines, which would require time-consuming post-processing.

It is important to note that even this small vectorized graphic needed some correction because of the usual faults of drawing by hand, such as uneven drawing lines. Moreover, compatibility problems among different vector graphic editors (for example in Inkscape) were discovered, as they displayed the final vector path differently.

An alternative method for vectorizing is to photograph the shape and then trace and draw the outline of the shape with a vector graphics editor, as applied by Casanovas (2011). The photograph must be of high quality (resolution, angle, optical deformation) for accurate results, and must be taken next to a photographic scale for digital scaling. This technique faces limitations, if the surface of the object is not completely flat but rounded or curved.[7]

Another possibility is surface measurement with 3D or 2D scanner technology. This approach is rather limited, because the extraction of lines and edges from the scanner's output point cloud is still a research topic today.[8] An aggravating factor is that the accuracy of the measurement depends greatly on the respective device, software and measurement conditions.[9]

In my approach to preparing the digital blueprint, the use of suitable software helped saving time. However, the digital realization is a time-consuming step in the work process and must be carried out carefully and diligently. Significantly accelerating the process requires expert knowledge.

Experimental

To assess the suitability of different lasers for their application in wood conservation and restoration, the main aim of this paper is to systematically examine the quality of the cut edges, the dimension and orthogonality of the cut kerfs as well as the size and repetition accuracy of laser-cut workpieces. Therefore, maple and walnut veneer (12% wood moisture; sanded up to 220 grit) of varying thickness (0.5, 2.5 and 6 mm) were cut with the following lasers:

- Pulsed-wave (pw) CO_2 laser
  λ=10.6 µm. Maximum laser power: 300 W. Motor-driven mirrors move the laser beam over the workpiece (laser scanner system) with a working distance of 189 mm and focal length of 200 mm. A cross-jet with lateral ejection of compressed gas is used.

- Continuous-wave (cw) CO_2 laser (figure 3).[10]
  λ=10.6 µm. Maximum laser power: 3 kW. A laser head moves the laser beam back and forth along the X and Y axes with a short working distance of 0.5 mm and focal length of 127 mm. Nitrogen from a coaxial jet flow is used as assist gas.

- Frequency-tripled Nd:YAG laser (pw).[11]
  λ=0.355 µm. Maximum laser power: 13 W. The laser beam is guided by optical fibers, the working distance is 225 mm. No assist gas.

The laser selection is based on examinations of wood with spectrophotometry, which showed that the maple and walnut veneers are highly absorbent (around 90%) at the wavelength of the CO_2 lasers (10.6 µm).[12] To extend the investigation a Nd:YAG laser is added. At the regular Nd:YAG laser wavelength of 1.064 µm the absorption rate is very low at around 10%. This is the reason why the frequency-tripled Nd:YAG laser with its shorter wavelength of 0.355 µm is employed, thus achieving a significantly higher absorption rate of 60-70%.

Figure 3 Cutting head of the CO_2 laser (cw).

Determination of laser parameters

Preliminary tests were conducted to determine optimal parameters for the combination of each laser, type of wood and wood thickness. Starting from customarily used settings the parameters like laser power and/or cutting speed got finetuned (that means usually increased). The aim was to just cut the wood, while minimizing negative side-effects like unnecessarily charring and burning. Several attempts were necessary to determine the final set of suitable laser parameters.

The preliminary tests already show that unsuitable Laser cutting parameters can easily lead to unsatisfactory results. If the energy impact is not high enough, the material is not cut, while cut edges and surfaces are badly charred if too much energy is used. It becomes clear that laser parameters determined for a specific thickness and wood species of veneer need further adaption if a different type of wood is cut.

Cutting in a multi-pass process (material is removed layer wise) can help reducing undesired pyrolytic reactions because the laser power per pass can be reduced and the workpiece can cool down in between. Placing the focal point below the surface leads to a higher cut quality when cutting thicker (6 mm) veneer.

No.	Laser type	Type of veneer, thickness (mm)	Laser power (W)	Frequency (kHz)	Cutting speed (mm/s)	Count of passes	Focal point position	Working distance (mm)	Cutting time (sec)	Gas assisted cutting
1.	CO_2-laser (pw)	Maple, 0.5	90	30	750	3	On the surface	198	~2	Cross jet: pressured air (0.5 bar)
2.	CO_2-laser (pw)	Walnut, 0.5	90	30	750	4	On the surface	198	~2	Cross jet: pressured air (0.5 bar)
3.	CO_2-laser (pw)	Maple, 2.5	125	30	750	15	On the surface	198	13	Cross jet: pressured air (0.5 bar)
4.	CO_2-laser (pw)	Walnut, 2.5	125	30	750	18	On the surface	198	15	Cross jet: pressured air (0.5 bar)
5.	CO_2-laser (pw)	Maple, 6	203	30	750	23	Centre of material	198	19	Cross jet: N_2 (0.5 bar)
6.	CO_2-laser (pw)	Walnut, 6	203	30	750	30	Centre of material	198	25	Cross jet: N_2 (0.5 bar)
7.	CO_2-laser (cw)	Maple, 0.5	420	cw	458	1	On the surface	0.5	~3	Coaxial jet: N_2 (0.5 bar)
8.	CO_2-laser (cw)	Walnut, 0.5	420	cw	458	1	On the surface	0.5	~3	Coaxial jet: N_2 (0.5 bar)
9.	CO_2-laser (cw)	Maple, 2.5	420	cw	458	1	On the surface	0.5	~3	Coaxial jet: N_2 (0.5 bar)
10.	CO_2-laser (cw)	Walnut, 2.5	420	cw	458	1	On the surface	0.5	~3	Coaxial jet: N_2 (0.5 bar)
11.	CO_2-laser (cw)	Maple, 6	900	cw	333	1	1 mm underneath the surface	0.5	~3	Coaxial jet: N_2 (2 bar)
12.	CO_2-laser (cw)	Walnut, 6	900	cw	333	1	1 mm underneath the surface	0.5	~3	Coaxial jet: N_2 (2 bar)
13.	Frequency-tripled Nd:YAG-laser (pw)	Maple, 0.5	1.1	50	30	3	On the surface	225	~3	–
14.	Frequency-tripled Nd:YAG-laser (pw)	Walnut, 0.5	1.1	50	30	2	On the surface	225	~3	–
15.	Frequency-tripled Nd:YAG-laser (pw)	Maple, 2.5	3.1	50	30	10	On the surface	225	90	–
16.	Frequency-tripled Nd:YAG-laser (pw)	Walnut, 2.5	3.1	50	30	15	On the surface	225	181	–

Table 1 Final laser cutting parameters.

The cut zone of the workpiece should have no contact with the worktable of the Laser cutting machine. Otherwise heat builds up below the workpiece, which leads to charring. In addition, the flow of debris out of the bottom of the cut kerf due to a coaxial gas jet is impeded. Moreover, the laser beam should not be reflected by the worktable, as this also produces heat marks on the bottom surface of the workpiece. Magnets and weights can be used to secure veneers in the Laser cutting machine's work area to avoid jigging caused by the gas stream. Results of my preliminary tests are provided in table 1. The table shows the Laser cutting parameters with the best cutting result for each laser type, material and thickness. These are the cutting parameters applied throughout the experiments and examinations in the following sections. Specific parameter settings are referred to via the ID numbers 1 to 16 in the first column of the table 1.

The frequency tripled Nd:YAG laser was not used with 6 mm veneer, because cutting would not have been possible within a reasonable timeframe.

Examination of cut edges

To systematically examine the quality of the cut edges the vectorized ornament (figure 2) was cut from 0.5, 2.5 and 6 mm thick maple and walnut veneer with the three lasers, using the parameter settings of table 1. To compare the lasers with traditional techniques the ornament was also hand-cut with a coping saw (saw blade of 0.26 mm thickness) from the 2.5 mm maple veneer.[13] The cut edges are qualitatively and subjectively assessed according to the following criteria by comparing the different results with each other.

- Minimal cut edge fillet:
  The edge should be sharp and not rounded. The sharper the edge, the better the rating.
- Minimal cut edge roughness:
  The cut edge should be smooth, clean and not need further treatment. The poorer the cut edge, the lower the rating.
- Minimal darkening/charring of the cut edge:
  The thermal decomposition of the material at the

Table 2 Cut edge quality.

Quality criteria	CO_2-laser (pw)						CO_2-laser (cw)						Frequency-tripled Nd:YAG-laser					
Wood type	M	W	M	W	M	W	M	W	M	W	M	W	M	W	M	W	M	W
Thickness (mm)	0.5	0.5	2.5	2.5	6	6	0.5	0.5	2.5	2.5	6	6	0.5	0.5	2.5	2.5	6	6
Complete cut out	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	X	X
Minimal cut edge fillet	–	–	–	–	–	–	○	○	○	○	+	+	+	+	+	+		
Minimal cut edge surface roughness	–	–	–	–	–	–	○	○	○	○	+	+	+	+	+	+		
Minimal darkening/charring of cut edge	+	+	+	–	+	+	○	○	○	+	–	–	–	–	–	○		
No darkening/charring of the top surface	✓	✓	✓	✓	X	X	X	X	X	X	✓	✓	✓	✓	✓	✓		
No darkening/charring of the bottom surface	✓	✓	✓	✓	X	✓	✓	✓	X	X	✓	X	✓	✓	✓	✓		

Meaning of the symbols and acronyms:

+	*Most satisfactory result of all lasers*	✓	*Criterion fulfilled*	M	*Maple*
○	*Second-most satisfactory result of all lasers*	*X*	*Criterion not fulfilled*	W	*Walnut*
–	*Least satisfactory result of all lasers*				

Figure 4 Varying degree of darkening of ornament cut edges (maple veneer 2.5 mm). From top to bottom: CO_2 laser (pw), CO_2 laser (cw), frequency-tripled Nd:YAG laser, hand sawn.

Figure 5 Cross-section of an ornament (maple veneer 6 mm) cut with the CO_2 laser (pw).

Figure 6 Top surface darkening (walnut veneer 6 mm). Top: CO_2 laser (cw); bottom: CO_2 laser (pw).

cut edge should be kept to a minimum. The less charring and darkening, the higher the rating.

- No darkening or charring on both top and bottom surface of the ornament along the cut line:
  The top and bottom surfaces of the ornament should keep their original appearance without darkening or charring. If visibly darkened, the criterion is not fulfilled.

Table 2 gives a comparative overview of the tested lasers across the various aspects of cut edge quality. To clarify how the lasers perform, the table should be read in horizontal direction, where rating symbols differentiate the best (+), second best (0) and least satisfactory (–) results. Because at 6 mm thickness only the two CO_2 lasers are employed and compared, the valuation symbols are solely '+' and '–'. Regardless of laser, parameters and wood type, the cut edges of all ornaments smell burned and are darkened to varying degrees (figure 4). At least minimal darkening and charring on the cut edges seem hard to avoid.
Looking in more detail at the results, the CO_2 laser (pw) appears to have the advantage that it produces on average the least darkened cut edges (figure 4). This may be an advantage of the multi-pass cutting with less power and the pulsed-wave mode, which leads to a well-controllable and shorter interaction time between laser beam and material. Closer examination of a cross-section of a 6 mm thick ornament cut by the CO_2 laser (pw) shows that the darkened area is just a thin coat and the inner part of the ornament is not affected by thermal changes (figure 5).
Cutting 6 mm, the upper surface of the ornaments is charred by the CO_2 laser (pw) (figure 6). Furthermore, the skewed angle of the cut edge is visible with the bare eye and the edges are the least sharp. Examining the cut edge roughness shows that the CO_2 laser (pw) induces small periodic surface structures/striation lines. The other two lasers produce smooth and clean-cut edges.

The CO_2 laser (cw) cuts all ornaments with the highest laser power in just one pass, which results in the shortest cutting time of approximately three second even for 6 mm thick ornaments (table 1, no. 7-12). However, in some applications the top and bottom surfaces of the ornament are slightly darkened and charred along the cut edge due to the higher temperature along the cut edge and especially at the tips of the shape. For the 6 mm thick ornaments the gas pressure (nitrogen) was increased from 0.5 to 2 bar and no charring occurred along the cut edges (figure 6). This indicates that a sufficiently pressurized inert coaxial gas jet can indeed help to prevent surface darkening and supports the cutting process.
The frequency-tripled Nd:YAG laser performs best on several criteria with the least laser power and shortest wavelength. The laser creates the sharpest and smoothest cutting edges and generates neither charring nor darkening on top or bottom of the ornaments without using any assist gas. Interestingly, the cut edges are colored very dark, though uniform (figure 4). A serious disadvantage caused by the low laser power and multi-pass cutting is the (comparably very) high cutting time. The frequency-tripled Nd:YAG laser needed three minutes to cut 2.5 mm thick walnut veneer (table 1, no. 16) and would not have completely cut through the 6 mm veneers within a reasonable timeframe.

Altogether, the temperature at the cutting zone produced by the laser seems to matter most for the quality of the cut edge. This temperature is determined by the material properties of the wood type in conjunction with the different laser parameters. Especially the two CO_2 lasers seem to significantly heat up the ornament (in comparison to the frequency-tripled Nd:YAG laser). This can cause undesired pyrolytic processes at and near the cut line, which can be controlled to some extend by the inert assist gas of the coaxial gas assist.

The hand-cut ornament shows no discoloration at all, but fine saw marks on the edge and splinters at the bottom cut line require further treatment (figure 4). Also, curves of the hand sawn cut line appear less perfect and the cutting process took almost nine minutes.

Examination of kerf width

The kerf width and perpendicularity of the cut edges are important factors for high-quality reconstructions and exact replacements. To investigate the kerf width and the cutting angle of the lasers, maple veneer of 2.5 mm was cut with the three lasers. The cutting parameters are given in no. 3, 9, 15 of table 1. Again, the Laser cutting was compared to hand-cutting with a coping saw.[14] Once cut, a digital microscope was used to measure the geometric features of the cut sections.[15] The lasers produce different kerf widths and angles determined by the amount of the material degraded during the cutting process. All cut kerfs of each laser are uniform, meaning there is no variation of kerf width within a cut line.

Results of the examination are presented in figure 7. It shows that the kerf width of the frequency-tripled Nd:YAG laser is the narrowest, while the CO_2 laser (pw) generates the widest. Independent of the laser type, the cut edges are neither parallel nor perpendicular to the surface and have tapered kerfs with a wider top. The frequency tripled Nd:YAG laser produces the most perpendicular cut of the three lasers. The hand sawn cut kerf corresponds exactly with the saw blade's thickness. Overall, the saw blade produces a parallel and perpendicular cut edge.

The two CO_2 lasers produce very different kerf widths and cutting angles, even though they have the same wavelength. It is noteworthy that the working distance and focal length varies widely between the CO_2 laser (cw) with 0.5 mm (focal length 127 mm) and CO_2 laser (pw) with 189 mm (focal length 200 mm). The experiment indicates that a shorter focal length can support a smaller spot size and hence a smaller kerf width. However, other factors may also play a role, such as type of focusing optics, type of assist gas system and count of passes.

My examinations suggest that the laser beam of frequency-tripled Nd:YAG laser with the shorter wavelength can be focused more efficiently and thus produces a finer focus spot diameter and kerf width than both CO_2 lasers with a longer wavelength. Thus, the frequency-tripled Nd:YAG laser is ideally suited for filigree work.

Examination of size and repetition accuracy

Size accuracy is crucial when producing exact wood replacements or inlays. The lasers should thus cut according to the programmed vector file and with high repetition accuracy; multiple cuts of the same shape should not vary.

To survey the size and repetition accuracy, three circles of 20 mm diameter were cut by coping saw and by the lasers from 2.5 mm thick maple veneer with the parameters no. 3, 9, 15 of table 1 without using kerf compensation. Kerf compensation provides the opportunity to compensate for removed material in the cut line that, if not compensated for, will cause an undersized workpiece in comparison to the actual vector file. To cut accurately, kerf compensation shifts the beam ½ diameter outside the programmed cut path. The size of the cut circles respectively circular blanks (CB) was precisely measured with a coordinate measuring machine and compared.[16] As already observed in the previous section, the laser-cut kerfs are non-perpendicular, so the top surface of the workpiece is slightly smaller than its bottom surface. Therefore, the bottom surface of the workpiece is measured, as it complies more with the programmed shape.

Both CO_2 lasers cut circular blanks slightly smaller than 20 mm, while the frequency-tripled Nd:YAG laser and the hand-sawing produce oversized workpieces (chart 1). As provided in table 3 the lasers cut with a deviation between ∅ -0.27 for the CO_2 laser (cw) and just ∅ 0.1 mm for the frequency-tripled

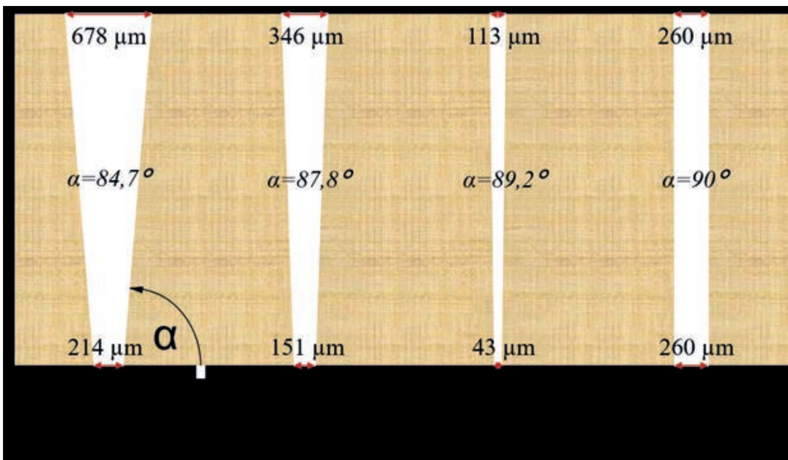

Figure 7 Diagram of the cut kerfs.

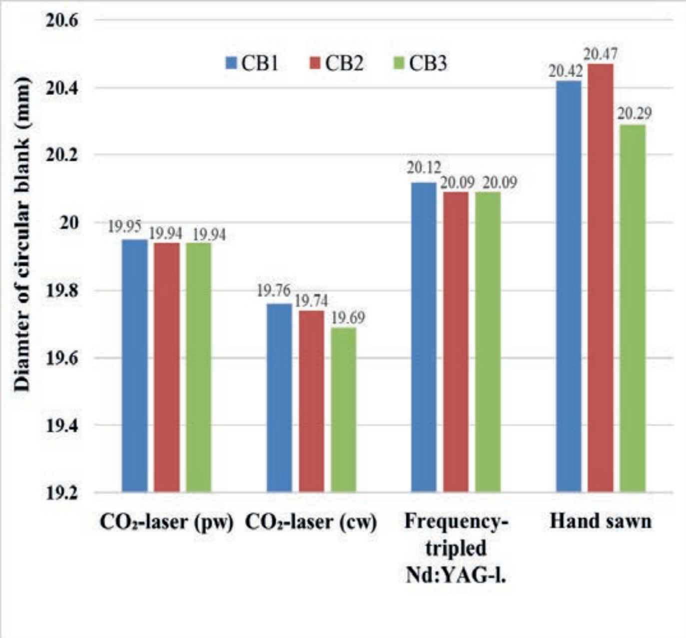

Chart 1 Measured diameters of the circular blanks.

Figure 8 Element of the wood-paneled ceiling decorated with marquetry (photo: Caroline Weiss).

Nd:YAG laser from the programmed circle of 20 mm. Hand-sawing produced an average oversize of ∅ 0.39 mm. Results indicate that the three lasers cut with a size accuracy that is significantly better than with hand-cutting.

The maximal deviation between the circular blanks or rather the repetition accuracy of each laser ranges between ∅ 0.01 for the CO_2 laser (pw) and ∅ 0.07 mm for the CO_2 laser (cw). The result of the hand-sawing is much poorer with an average deviation of 0.18 mm between the three attempts (table 3). Admittedly hand-cutting is somewhat prone to the 'human factor', in particular personal skills.
Combining and comparing the findings of the kerf width and size accuracy tests, it becomes clear that the measured kerf width and the under-/oversize are not coherent. In theory and because kerf compensation was turned off, one would have suspected circular blanks with a minimal allowance of ½ kerf width. Possibly, thoroughly recalibrating the laser devices before cutting could lead to the expected (or even more accurate) results. Overall, all lasers have a higher size and repetition accuracy than hand-cutting.

Case study survey

In order to broaden the perspective and determine common reasons for and problems with the application of the technology, a qualitative survey on four projects that utilized the Laser cutting technology successfully for reconstructing marquetry, parquetry and replacing losses of veneer and other materials was conducted. The survey was based on interviews with each project manager as well as the corresponding publication that was available in one case.
Weißmann (2006) reconstructed missing parts of tortoiseshell, painted paper and brass from a Boulle marquetry which can be difficult and delicate to process.[17] The conservation workshop C. Weiss Conservation in Hamburg reconstructed in 2012 elements of a wood-paneled ceiling which were decorated with complex shaped marquetry by laser cutting.
In 2015 Hirschfelder Parkett GmbH reconstructed a historical panel parquet of 43 m2 consisting of a repeating parquet element in a manor house in Germany. The wood wear layer of 8 mm was, once programmed, cut in a short time. The company regularly employs Laser cutting technology to manufacture parquet floors.

Table 3 Size and repetition accuracy.

Circular blanks	CO_2-laser (pw)	CO_2-laser (cw)	Frequency-tripled Nd:YAG-laser	Hand sawn
Average diameter of the circular blanks (mm) $(CB1 + CB2 + CB3)/3 = CBØ$	19.94	19.73	20.10	20.39
Average deviation of the programmed circle/ size accuracy (mm) $20\ mm - CBØ = Ø\ dimensional\ deviation$	-0.06	-0.27	0.10	0.39
Max. deviation between the circular blanks/ repetition accuracy (mm) $CB_{max.} - CB_{min.} = max.deviation$	0.01	0.07	0.03	0.18

Also in these Proceedings, Simon Brown (Conservation Letterfrack, Ireland) writes about employing the Laser cutting technology for replacing over 400 losses of veneer of over 13 different types of wood in a bureau-bookcase. All projects employed different CO_2-lasers for cutting. This illustrates the versatility of CO_2 lasers, because they were successfully applied to cut different types of material (organic and inorganic) with varying thickness (veneer from 0.5 to 8 mm).

The project managers, who often had no or little expertise in laser cutting, gained the following experience:

- Employing CO_2 lasers is affordable, as they are readily available at model workshops, universities or specialized companies and institutes. Choices vary greatly with regard to laser power, machine table dimensions and costs for the utilization/acquisition. These and many more factors have to be considered when choosing the appropriate laser for a project.
- In comparison with sawing by hand, laser cutting is significantly faster. However, the digital realization in the Laser cutting workflow is very time-consuming. It can be done in various ways, but may require special software like CorelDraw or AutoCAD, expert knowledge and a diligent execution.
- Once prepared, the digital file can be modified, corrected, copied and cut as often as required.
- In most cases the conservators hired experts for digitalization and the actual cutting, together with the Laser cutting machine. In one project, the rented laser machine was operated independently by an employee after being appropriately instructed. In rare cases the costs for the purchase of a laser cutter may be worthwhile.
- The cut edges of veneers are splinter-free and do not require post-processing. They are, however, not fully rectangular to the surface, slightly charred and darkened.
- By choosing the right process parameters, undesired thermal impact can be reduced, but not prevented.
- Darkening of the workpiece surface can be removed by sanding.
- To hide the burned cut edges the attribute of non-orthogonal kerfs can be utilized. Before cutting, the vector-image must be mirrored, and the resulting workpieces are fitted in upside down (or reverse). Because of the angularity, the burned cut edges are covered and not visible.
- Laser cutting is predestinated for cutting complex shapes in materials that are difficult or delicate to process, because cuts can be made in almost any direction and the material is not mechanically stressed.
- When trying to cut wavy veneer, the material must be flat and secured during the cutting process to prevent unequal and incorrect cutting lines.

Figure 9 Element of the panel parquet (Photo: Bernhard Assing).

Overall, every project had significant time and cost savings in carrying out the projects by laser (as compared to traditional handcraft such as hand sawing) due to the high cutting speed and the size accuracy of workpieces. Without laser cutting the projects would not have been executed so (comparably) easily.

Ethical consideration

New technologies provide new possibilities. On the other hand, the knowledge and experience of craftsmanship is a very important part in the theoretical and practical training of conservators. This knowledge helps to understand construction methods and traditional processes. It enables to restore objects such as furniture consistent with their historical characteristics. It was not without reason that in 2002 UNESCO adopted intangible cultural heritage 'as a mainspring of cultural diversity and a guarantee of sustainable development'.[18] Nonetheless, skilled craftsmanship requires a wealth of experience and expertise and can be time-consuming. This means that using traditional techniques may be rather uneconomical, which creates a challenge for the conservator. The employment of modern technologies like the speedy process of laser cutting can be one solution to this problem. By

using this efficient technology even costly projects may become economically reasonable.
Furthermore, the Laser cutting technology offers the advantage of very accurate work. So, supposedly there is no longer any need for removing original material to match the area of a loss. Additionally, the darkened cut edges produced by the laser allow identifying the replacements relatively easily. This can be seen in accordance with the Venice Charter Article 12, which states: 'Replacements of missing parts must integrate harmoniously with the whole, but at the same time must be distinguishable from the original so that restoration does not falsify the artistic or historic evidence.'[19]
Neither the Venice Charter nor the European Confederation of Conservator-Restorers' Organisations (E.C.C.O. Professional Guidelines) (I and II) reject the use of modern technology. In fact, E.C.C.O. Professional Guidelines claim: 'The conservator-restorer must strive to enrich her/his knowledge and skills with the constant aim of improving the quality of her/his professional work.'[20] Beyond the technical benefit it is, however, necessary to strive for a balance between craftsmanship and modern technology.

Conclusion

Laser cutting technology is a useful modern tool in wood and furniture conservation and restoration, for producing reconstructions and replacements, even for complex shapes and different types of wood/material. The laser cuts at high speed and precision and can balance a lack of manual skills. The digital preparation can be done in various ways but takes much longer than the cutting process itself and requires expert knowledge. The vector file for cutting can be modified and corrected quickly as often as required, which makes it very efficient, compared to traditional woodworking methods.
Laser cutting is a contactless process, which means even brittle and hard to process materials can be cut in almost any direction. The smooth, flat and splinter-free cutting edges do not need further treatment. The not perfectly perpendicular cut edges with various levels of darkening as well as the uniform cut lines produced by the laser are down-sides but could also be to the conservator's advantage. They allow distinguishing the reconstruction from the original substance, thus fulfilling conservation ethical demands regarding the visibility of newly inserted material and also prevent counterfeiting.
Each laser type has its own strengths and weaknesses: The laser should be selected based on the type of material and its thickness as well as the particular goals and framework of the project. Finding suitable laser parameters can require a series of tests, depending on the experience and available support. Purchasing a laser cutting machine and spending money on training does at this stage not seem efficient and may limit the possibility to select different lasers for different projects.
In the experiments described in this paper CO_2-lasers achieve good overall results at all types of veneer and thicknesses, but apparently heat up the workpiece more than the frequency-tripled Nd:YAG laser. Therefore, the frequency-tripled Nd:YAG laser is more apt to cut heat-sensitive materials and small, filigree shapes, in which case its higher cutting times matter less.
The case studies show that CO_2 lasers are often used for wood and furniture conservation projects. All projects have been successful, and users were generally satisfied with the performance of the lasers.
Overall, employing the Laser cutting technology seems reasonable, if the following conditions are met:

- Project contains a high cutting time.
- Complex shapes need to be cut.
- Material is brittle and difficult to cut.
- Lack of skilled hand-sawing expertise.
- Simple, fast and multiple corrections/adjustments of the shape to be cut.
- The same workpiece needs to be produced in high amounts

Overall, the Laser cutting technology has high potential for fulfilling specific wood conservation needs and it can be expected to be employed more often, especially in large monument preservation projects and for time-saving/economic reasons.

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Notes

[1] Exceptions are amongst others: E.J. Casanovas, 'Can laser cutting be an alternative technique for marquetry completion in furniture conservation?', student essay/thesis, Linköpings Universitet, Furniture Studies, Stockholm, 2011; and V. Thelin, 'Laserskuren intarsia: ett komplement till äldre intarsiatekniker', student essay/thesis, Linköpings Universitet, Furniture Studies, Stockholm, 2010.
[2] Compare: W.M. Steen, *Laser Material Processing*, Springer Verlag, 1991 (Chapter 1-2), and J. Powell, *CO_2 laser cutting*, Springer Verlag, 1993, Chapter 1.
[3] Compare: Steen 1991, Chapter 1; Powell 1993, Chapter 8.
[4] Compare: Steen 1991, Chapter 3; Powell 1993, Chapter 4.
[5] M. Merkel, K.-H. Thomas, *Taschenbuch der Werkstoffe*, Fachbuchverlag Leipzig 1994, pp. 480-481.
[6] Compare: Steen 1991, Chapter 2-3; Powell 1993, Chapter 2, 4.
[7] Casanovas 2011, 30.
[8] W. Boehler, A. Marbs, 'Investigating Laser Scanner Accuracy', in: *Proceedings of the XIXth International Symposium, CIPA 2003, New perspectives to save cultural heritage*: Antalya (Turkey), 30 September-04 October 2003, Edited by M.O. Altan, 2003.
[9] T.P. Kersten, 'Untersuchungen zur Qualität und Genauigkeit von 3D-Punktwolken für die 3D-Objektmodellierung auf der Grundlage von terrestrischem Laserscanning und bildbasierten Verfahren', (dissertation) Technische Universität Dresden, 2017, pp. 1, 132.
[10] Cutting head Precitec AK HP 1.5 E. (f5").
[11] AVIA-Machine, 3D MicroSTRUCT ns.
[12] Cary 5000 UV-VIS-NIR spectrophotometry.
[13] Saw blade NIQUA FIX BLUE: 0.26 x 0.63 x 130 mm.
[14] Saw blade NIQUA FIX BLUE: 0.26 x 0.63 x 130 mm.
[15] Keyence VHX-5000 digital microscope.
[16] WERTH VIDEO-CHECK IP400 CNC Coordinate Measuring Machine (9000 measurement points per circular blank, roundness measurement method: Least Square Circle LSC).
[17] R. Weißmann, 'Teilrestaurierung eines Berliner Tisches um 1850 in Boulle-Marketerie unter Einsatz der Lasertechnologie', (diploma thesis) University of Applied Sciences Potsdam, 2006.
[18] https://ich.unesco.org/en and http://www.unesco.org/new/en/member-states/single-view/news/brochures_linking_intangible_cultural_heritage_with_sustaina/ [10/10/2018].
[19] ICOMOS, International Charter for the Conservation of Monuments and Sites (The Venice Charter) adopted by ICOMOS in 1965, article 12.
[20] European Confederation of Conservator-Restorers' Organizations, E.C.C.O. Professional Guidelines (II), Code of Ethics, article 12.

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- Figure 3-6: Astrid Beling
- Figure 8: Caroline Weiss
- Figure 9: Bernhard Assing
- Tables, diagrams and chart: Astrid Beling