Radial scanning strategies leading to substantial improvements in processing time

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ABSTRACT

Synchronizing a laser system and its ultrashort laser pulses with a galvanometer scanner results in the highest precision and throughput currently achievable. Traditionally, these synchronized systems use linear scanning strategies to structure a surface. Due to the acceleration and deceleration phase at the end of each line, the efficiency of this method is limited. Novel radial strategies have been developed to overcome this limitation. Recent tests with these newly developed machining paths have shown that process time gains of up to 300% can be achieved compared to conventional linear scanning while still being fully synchronized. Various radial patterns such as circles and spirals were analyzed and developed. These individual methods were further optimized to achieve the highest possible process speeds and reduce times where the laser is not in operation. These newly developed paths were evaluated for their efficiency compared to conventional linear paths. Furthermore, the system was extended by an optical Z-axis, with which the focus of the laser beam can be dynamically readjusted during the process. This now makes it possible to mark workpieces with uneven surfaces while maintaining full synchronization between the scanner and the laser system.

Keywords: Marking strategy, Synchronized mode, Processing time, Galvo Scanner, Radial machining

1. INTRODUCTION

Increasing the throughput of surface structuring with ultrashort laser pulses can be achieved by various approaches. On one hand, the laser pulse parameters can be changed. For example, the pulse energy can be increased. However, publications[1] show that the optimal pulse energy depends on the spot radius and the threshold fluence of the material to be processed. Another approach is to change the deflection of the laser beam, such as increasing the pulse-to-pulse distance. But this is also limited by the need of an optimal surface structure. For the optimal surface structure, it is half of the spot radius[2]. Another possibility is to increase the scanning speed or changing the scanning strategy, which this paper focuses on.

There are various strategies for marking a surface, each with their own advantages and disadvantages. One traditional method is using a synchronized system with a linear scanning strategy[1,2], which involves scanning the laser horizontally across the workpiece and gradually increasing the vertical position. This strategy is simple to implement as it can be done using a cartesian coordinate system and it is easy to imagine the positions being approached. However, the major disadvantage is the time lost during turns, where the laser movement needs to be slowed down, reversed and re-accelerated. Despite various optimization techniques[1,3], such as bidirectional scan mode, where odd lines are marked in the opposite direction of even lines, a significant amount of process time is still lost. Another method is the shifted laser[4,5] surface texturing, which distributes the pulses to the entire processed surface by fast scanning on straight lines.

In this work, a new strategy, the radial form, was investigated. Instead of scanning the workpiece vertically and horizontally, a radial path is followed, with particular focus on circular and spiral movements. This strategy has the advantage of eliminating the need for jerky changes of direction, where the laser beam needs to be re-accelerated. Instead, it only needs to be accelerated once at the start and can then be continuously deflected. This newly developed strategy is fully compatible with the synchronization technique[5] used in our lab, allowing for high-precision marking of individual pulses over multiple layers. The radial form strategy can improve the throughput of surface structuring by eliminating the time loss during turns and allowing for continuous deflection of the laser.

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2. THEORY

2.1 Constraints of the laser machining system

A limitation of all scanning systems is the minimum radius that can be marked, which is especially significant for radial machining. This limit is primarily determined by the dynamics of the scan head used. One of the main constraints is the constant acceleration that occurs in a circular path, which must not exceed the maximum capability of the scan head. The acceleration can be calculated from the velocity and radius of the circular path. The speed of deflection (tangential speed) is determined by the chosen point distance and repetition rate, which are independent of the radius. In each repetition, the laser must be deflected by the point distance, as depicted in the following formula 1.

$$r_{min} = \frac{v^2}{a_{max}} = \frac{(pitch*f_{rep})^2}{a_{max}} \tag{1}$$

Where r_{min} is the minimum radius that can be marked, pitch is the distance between each pulse, f_{rep} is the repetition rate and a_{max} is the maximum acceleration of the scanning system.

Another limitation arises from the jerk. This describes the maximum possible rate of change of the given acceleration. The formula for the jerk resulting from a circular acceleration is derived from the derivation of the acceleration formula with respect to the time.

$$r_{min} = \sqrt{\frac{v^3}{a_{max}}} = \sqrt{\frac{(pitch*f_{rep})^3}{a_{max}}} \tag{2}$$

The diagrams in the Figure 1 show the results for two different repetition rates. Calculations were made with a scanning system that can accelerate at 32'000 m/s^2 and has a maximum jerk of 1'000'000'000 m/s^3. It can be seen that at low repetition rates the radius is limited exclusively by the jerk, while at higher repetition rates it is limited by the acceleration.

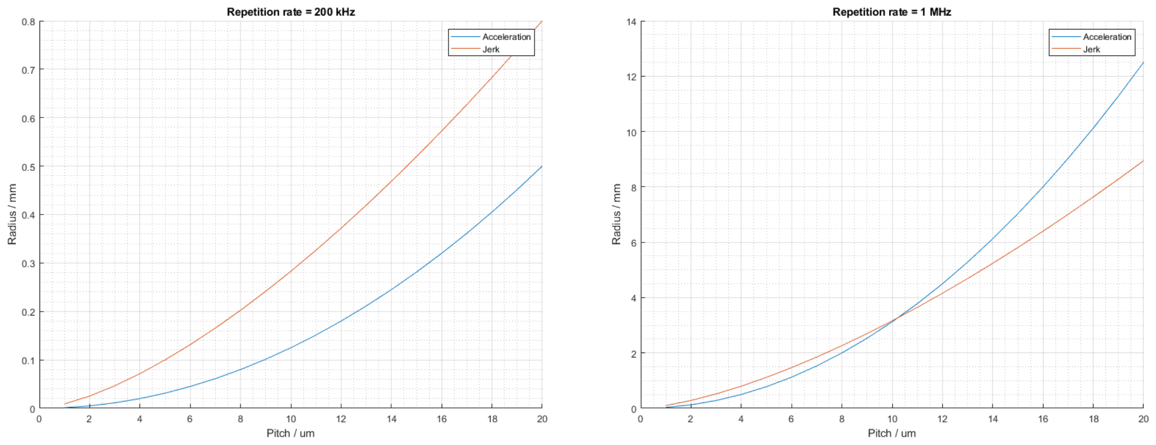


Figure 1. Radii limited by an acceleration of 32 000 m/s^2 and a jerk of 1 000 000 m/s^3

2.2 Spiral movement

The radial process of spiral machining was studied, with a focus on the examination of various spirals. One spiral of interest is the Archimedean spiral, which has the unique property that a ray emanating from the origin intersects the spiral's turns at equidistant points. This results in consistent point spacing between the spiral's loops, as demonstrated in Figure 2.

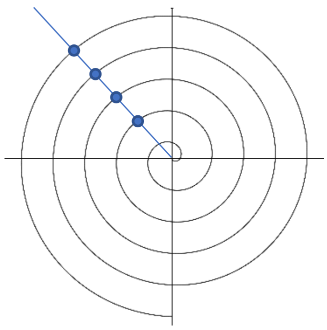


Figure 2. Illustration of an Archimedean spiral

Formula 3 shows the basic equations for an Archimedean spiral in the Cartesian format. However, as illustrated in Figure 3a, the equation yields non-uniformly spaced points on the spiral as the parameter φ linearly increased.

$$x(\varphi) = k * \varphi * \cos(\varphi)$$
$$y(\varphi) = k * \varphi * \sin(\varphi) \tag{3}$$

Using a lengthy mathematical analysis and approximating the angle, the formula 4 was derived. This shows in which steps φ has to be increased in order to obtain an equally distributed spiral.

$$\varphi_2 = \varphi_1 + \frac{s}{a * \sqrt{1 + {\varphi_1}^2}} \tag{4}$$

As demonstrated by the results in Figure 3b, the application of this method results in a spiral with uniformly spaced points.

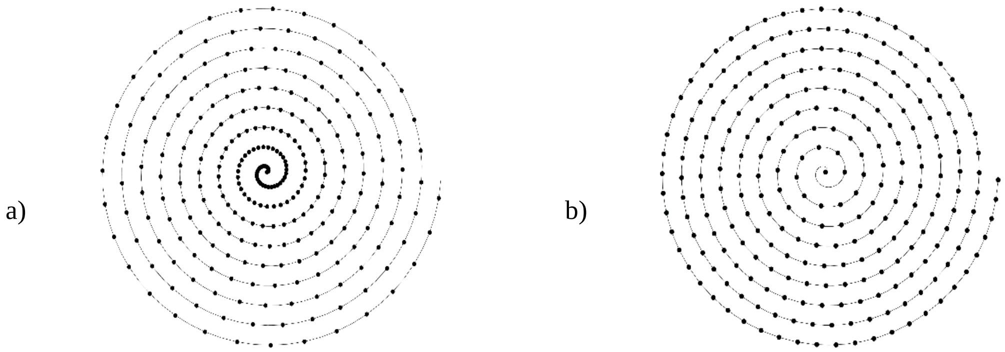


Figure 3. a) Archimedean spiral with unevenly distributed points, b) evenly distributed points

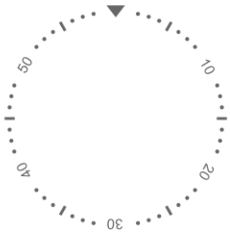
3. EXPERIMENTAL SET – UP

The PicoBlade 2 from Lumentum, which generates 10 ps pulses with a variable repetition rate and a wavelength of 1064 nm, was used as the laser system. A 163 mm focusing objective was utilized, resulting in a spot radius of 10 µm. The excelliScan 14 was employed for beam deflection, allowing for acceleration of 32’000 m/s^2 and a maximum jerk of 1’000’000 m/s^3. All experiments were performed with laser movement (deflection) synchronized[5] to the laser clock.

3.1 Processing time

To compare the two types of processes, four distinct patterns were selected: a square, a cross, a circular ring, and a bezel. Two linear patterns and two radial patterns were chosen to determine whether radial machining is only advantageous for specific structures or can be applied to a wide range of structures. Table 1 presents an overview of the chosen test patterns. The square pattern was selected as it is a commonly used in ablation studies. The cross pattern is beneficial for linear machining due to its straight edges. The circular ring is well-suited for radial machining. Lastly, the bezel of a watch is a prime example of a structure that is ideal for radial machining.

Table 1. Selected test patterns

	Square	Cross	Circular ring	Bezel
				
Structure	Linear	Linear	Radial	Radial
Width	50 mm	50 mm	50 mm	45 mm
Height	50 mm	50 mm	50 mm	45 mm
Filling level	100 %	55.5 %	58.9 %	1.9 %

These four patterns were each compared with three different repetition rates and pitches. The selected repetition rates were 200 kHz, 1 MHz, and 2 MHz. These are the most common rates used in our lab. For pitches, 3.7 µm, 12 µm, and 25 µm were chosen. These values cover a range from small to larger structures. With these parameters, all patterns were marked using the linear marking strategy and the new radial strategy. The process time was recorded in each case to make a comparison between the two methods.

The following settings were used for linear ablation:

- Movement by means of microvectors[3]
- Variable line length optimization[3]
- Bidirectional in scan direction[4]
- Bidirectional in cross scan direction[4]

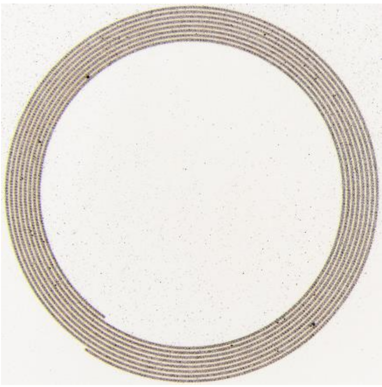
In radial machining, the minimum radius is the only adjustable parameter. This radius was set to the minimum value allowed by the pitch and repetition rate according to formula (2).

4. RESULTS

4.1 Radial path

To evaluate the system's precision and the effectiveness of synchronization, the same pattern was marked on over 100 layers. The marking was performed at a repetition rate of 400 kHz and a pitch of 60 um, as shown in Figure 4. In Figure 4a, the entire path is visible, and in Figure 4b, a magnified section is shown. The individual points remain distinct and consistently spaced even after multiple layers of ablation, indicating that the points were precisely placed in the same location on each layer, thus confirming the success of the movement to the laser clock synchronization.

a)



b)

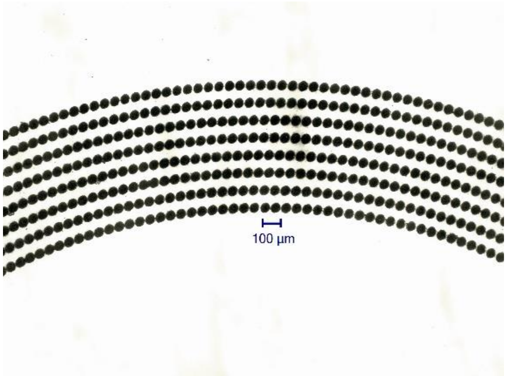
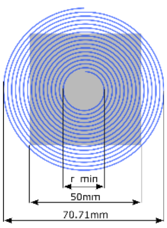
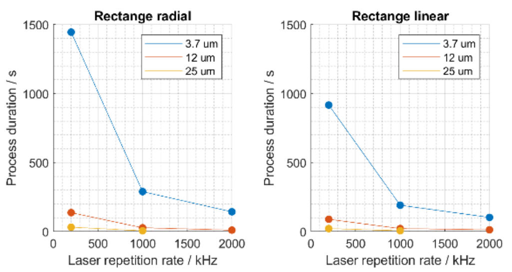


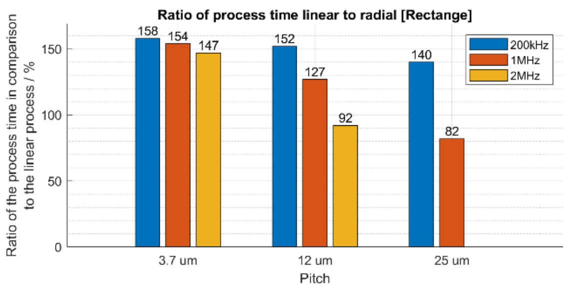
Figure 4. Marked spiral trajectory with 100 layers, 60 µm point-to-point spacing and 100 µm between the loops

4.2 Rectangle processing time

The rectangle pattern is not well-suited for radial machining because it leaves a hole in the center of the structure, resulting in an incomplete surface marking. This hole is caused by the limited acceleration of the scanner. Additionally, the shape of the rectangle itself poses a challenge when working on the corners in a circular fashion, as it requires larger radii than the rectangle's width. This is illustrated in Figure 5. In this experiment, a rectangle with an edge length of 50 mm was used, and to cover it completely, a spiral with a diameter of at least 70.71 mm is needed. However, on these outer radii, radial machining is inefficient as much of the time is spent on traveling over un-marked surfaces. Linear machining has a clear advantage in this case as it only moves over positions that need to be marked.







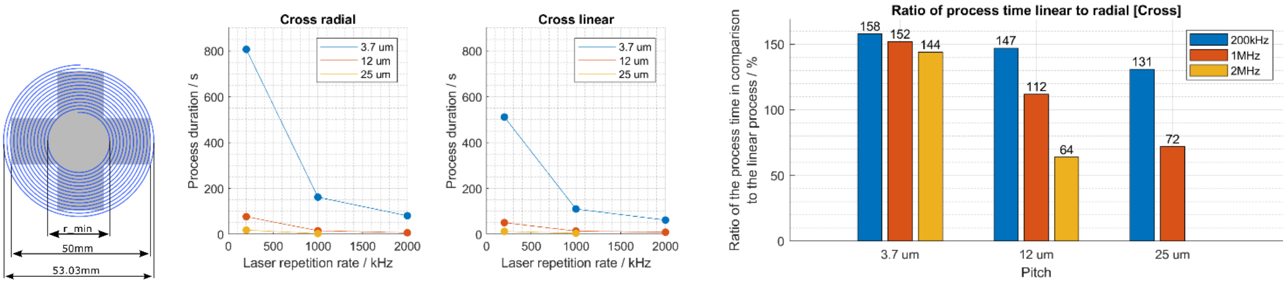
a) b) c)

Figure 5. a) The rectangle superimposed with a radial trajectory. b) Processing duration for machining a 50mm x 50mm rectangle (left: radial machining, right: linear machining). c) Comparison of processing durations between a radial and a linear process using a rectangle structure

The Figure 5b illustrates the comparison of the processing time for radial and linear machining of the rectangle. It can be observed that radial processing is slower than linear processing for most settings. Only at high repetition rates and large pitches is radial processing on par or even faster. The Figure 5c more clearly illustrates this difference, as it shows the ratio of machining durations. At 3.7 µm, radial processing is slower by almost one half. The difference becomes smaller at higher frequencies, but this is not only due to the faster marking speed but also due to the minimum radius that can be achieved. At higher frequencies and larger pitches, the minimum radius that can be radially processed becomes bigger. This means that at higher repetition rates or pitches, fewer points can be machined radially as the hole in the center becomes larger.

4.3 Cross processing time

The cross pattern shares similar characteristics to the rectangle. The challenge of oversized radii needed to reach the corners is also present here, but it is highly dependent on the chosen proportions of the cross. As illustrated in Figure 6a, for the selected cross, the required radius is only slightly larger than the pattern itself.



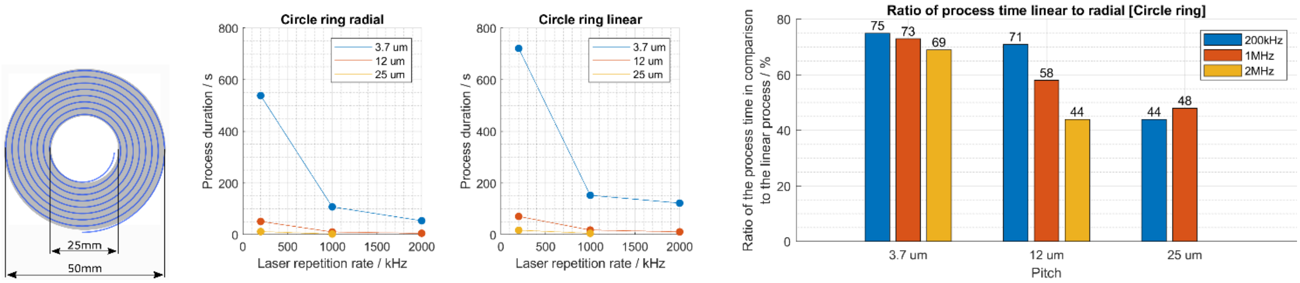
a) b) c)

Figure 6. a) The cross superimposed with a radial trajectory. b) Processing duration for machining a 50mm x 50mm rectangle (left: radial machining, right: linear machining). c) Comparison of processing durations between a radial and a linear process using a cross structure

The processing durations are similar to those of the rectangle. Figure 6a and 6b illustrates the measurement results. The machining time for both techniques is shorter than for a rectangle. However, the linear process is generally faster, except for large pitches and high repetition rates.

4.4 Circle Ring processing time

The circular ring is a radial pattern that is well-suited for radial machining. The challenge of the minimum radius is eliminated by the inherent hole in the center of the shape. The spiral path can be effectively placed on the ring, as illustrated in Figure 7a, without traversing over un-marked areas. At the same time, this pattern is less optimal for linear machining. The laser must travel over the un-marked space in the center, resulting in decreased efficiency



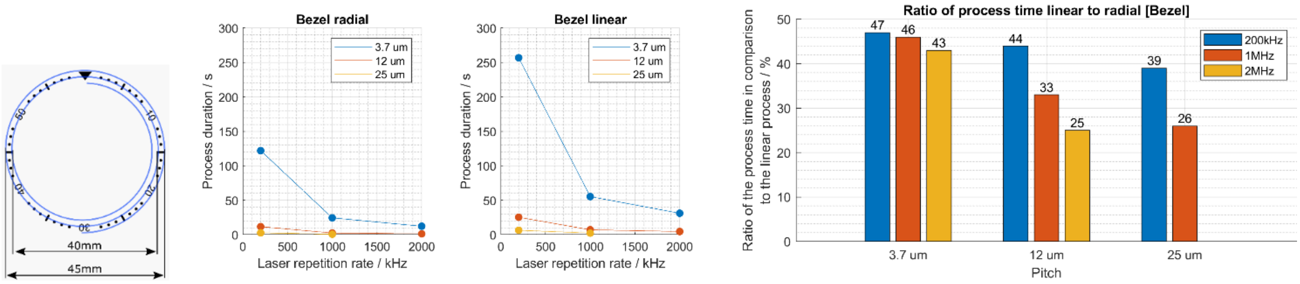
a) b) c)

Figure 7. a) The circle ring superimposed with a radial trajectory. b) Processing duration for machining a 25mm/50mm circle ring (left: radial machining, right: linear machining). c) Comparison of processing durations between a radial and a linear process using a circle ring structure

These effects can be clearly observed in the processing durations, as illustrated in the Figure 7b. Although the pattern is similar in size to the cross, the linear process now takes over 700 seconds, instead of approximately 500 seconds. The opposite is true for the radial process. The Figure 7c illustrates this even more clearly, the radial process is consistently faster than the linear process. At specific settings, it is even more than twice as fast.

4.5 Bezel processing time

The bezel is similar in shape to the circular ring, with the only difference being that the ratio of the hole in the center to the ring to be machined is even smaller for the bezel than for the circular ring used. Consequently, the radial process is the clear preference for this shape.



a) b) c)

Figure 8. a) The bezel superimposed with a radial trajectory. b) Processing duration for machining a 40 mm/45 mm bezel (left: radial machining, right: linear machining). c) Comparison of processing durations between a radial and a linear process using a bezel structure

Figure 8b and 8c shows that the radial process is at least twice as fast in all tests. For certain scenarios, an acceleration of the processing time by more than 300 % can be achieved.

5. CONCLUSION AND OUTLOOK

The presented marking strategy represents a significant advancement in terms of machining time. Comparisons were made between the classic linear process and the spiral process in terms of process time, and it was shown that for certain structures, the radial process can achieve a substantial speed advantage. For example, marking a watch bezel with 12um pitch and 1 MHz repetition rate takes only 2.3 seconds instead of 7 seconds, a significant improvement of over 300%. Further optimization such as using variable spiral size could potentially lead to even greater improvements. One could also consider an even more innovative strategy, such as mathematically optimizing the marking path, which is significantly different from traditional raster scanning and may lead to even faster machining.

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