Research Article

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Adaptive optical beam shaping for compensating projection-induced focus deformation

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Abstract: Scanner-based applications are already widely used for the processing of surfaces, as they allow for highly dynamic deflection of the laser beam. Particularly, the processing of three-dimensional surfaces with laser radiation initiates the development of highly innovative manufacturing techniques. Unfortunately, the focused laser beam suffers from deformation caused by the involved projection mechanisms. The degree of deformation is field variant and depends on both the surface geometry and the working position of the laser beam. Depending on the process sensitivity, the deformation affects the process quality, which motivates a method of compensation. Current approaches are based on a local adaption of the laser power to maintain constant intensity within the interaction zone. For advanced manufacturing, this approach is insufficient, as the residual deformation of the initial circular laser spot is not taken into account. In this paper, an alternative approach is discussed. Additional beam-shaping devices are integrated between the laser source and the scanner, and allow for an *in situ* compensation to ensure a field-invariant circular focus spot within the interaction zone. Beyond the optical design, the approach is challenging with respect to the control theory's point of view, as both the beam deflection and the compensation have to be synchronized.

Keywords: active and adaptive optics; beam shaping; laser materials processing.

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1 Introduction

For the processing of extended working surfaces, scanning-based methods have been established [1]. Particularly, galvanometer scanners are applied that deflect the laser beam either in front of an F-theta lens (pre-objective scanning) or directly behind a focusing lens (post-objective scanning). For the processing of three-dimensional (3D) working surfaces, the scanning unit is often supplemented with an additional active optical system that compensates for the occurring focus shift.

If the laser beam hits the 3D surface, the initial typically circular laser spot is influenced by projection mechanisms. Subsequently, the spot is approximately elliptically deformed, whereas the degree of deformation correlates with the inclination angle δ the laser beam includes with the surface normal. The situation is depicted in Figure 1 for a pre-objective scanning system.

The deformation cannot be compensated by presently available optical systems. As the deformation results in an increasing interaction area, frequently pursued compensation methods are based on a local variation of the laser power to maintain a constant intensity [2]. As the spot size is not taken into account, the compensation may not be sufficient for sensitive applications such as laser polishing [3] or surface structuring by laser remelting [4, 5]. These applications necessitate a constant melt pool volume that is obviously disturbed by any deformation of the laser spot. Concerning surface structuring by laser remelting, previous work has shown that the process quality decreases at inclination angles above 20° [4].

This motivates a completely new approach for the compensation for projection-induced focus deformation applying adaptive optical beam shaping.

2 Adaptive optical beam shaping

The general principle is schematically depicted in Figure 2 [6].

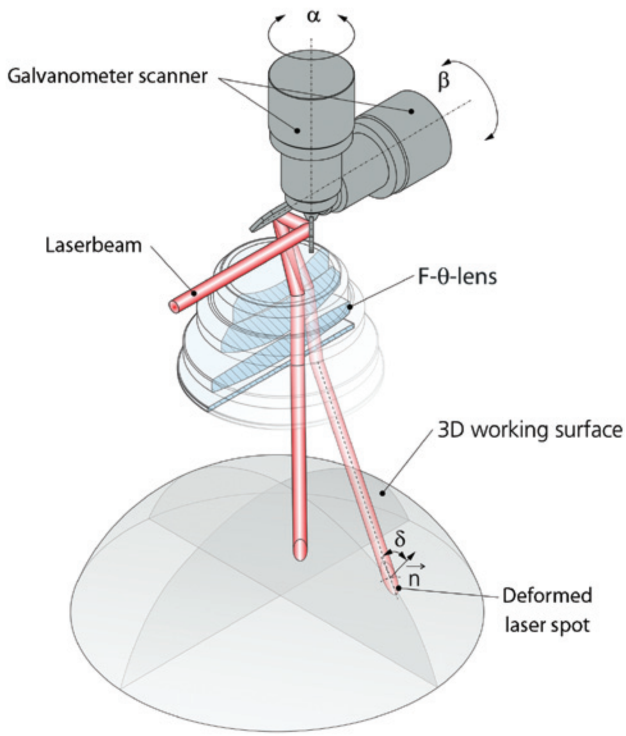

Figure 1: Schematic depiction of the projection-induced focus deformation for the processing of a surface with a spherical shape.

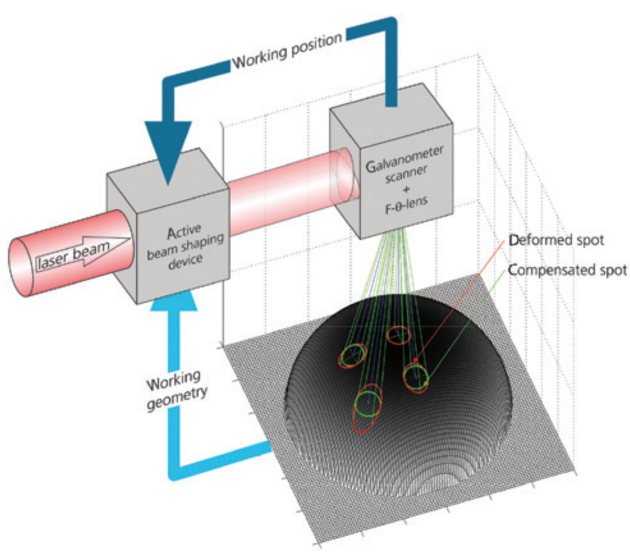

Figure 2: Schematic depiction of the general principle for the compensation of focus deformation.

An additional active beam-shaping device is integrated between the radiation source and the scanning unit. Compensation takes place by modulating the laser beam specifically to the amount of deformation in the interaction zone. As the deformation alters with the working position and the working geometry, the beam shaping is synchronized with the scanning unit. The deformation of the focal spot in the interaction zone is not continuously detected by a measurement device such as a camera. Instead, an open-loop architecture is pursued that adapts the amount of beam shaping autonomously to the working position and for an initially known working geometry.

In the following, an in-depth analysis of the projection mechanisms is carried out. It enables a quantification of the deformation for a given working geometry and working position. The results serve the active optical system design and the control design as boundary conditions.

2.1 In-depth analysis of the projection mechanisms

For the quantification of the deformation, an intersection curve is evaluated. It encircles the area the laser beam irradiates on the surface. A suitable approach for the evaluation of this curve is the interconnection of penetration points of a number of individual rays with the surface. Their propagation through the galvanometer scanner and the F-theta lens is calculated vector-analytically and is schematically depicted in Figure 3.

A single ray enters the scanning unit. The vector

$$\vec{r}(\tau)=\frac{\begin{bmatrix}-\theta_x\cdot\cos\tau\\ -1\\ -\theta_z\cdot\sin\tau\end{bmatrix}}{\left\|\begin{bmatrix}-\theta_x\cdot\cos\tau\\ -1\\ -\theta_z\cdot\sin\tau\end{bmatrix}\right\|}$$

designates its direction. θ_x and θ_z describe the residual divergence of the laser beam in two orthogonal directions. To calculate the vector $\vec{I}_R$, the distortion of both the galvanometer scanner and the F-theta lens have to be taken into account [7]. $\vec{I}_R$ is determined by

$$\vec{I}_R=\begin{bmatrix}-1&0&0\\0&-1&0\\0&0&1\end{bmatrix}D_{Ry}(\beta)\cdot D_{Rz}(\alpha)\cdot\vec{r}.$$

$$D_{Rz}(\alpha)=\begin{bmatrix}\cos\left(-2\alpha+\frac{\pi}{2}\right)&-\sin\left(-2\alpha+\frac{\pi}{2}\right)&0\\ \sin\left(-2\alpha+\frac{\pi}{2}\right)&\cos\left(-2\alpha+\frac{\pi}{2}\right)&0\\ 0&0&1\end{bmatrix},$$

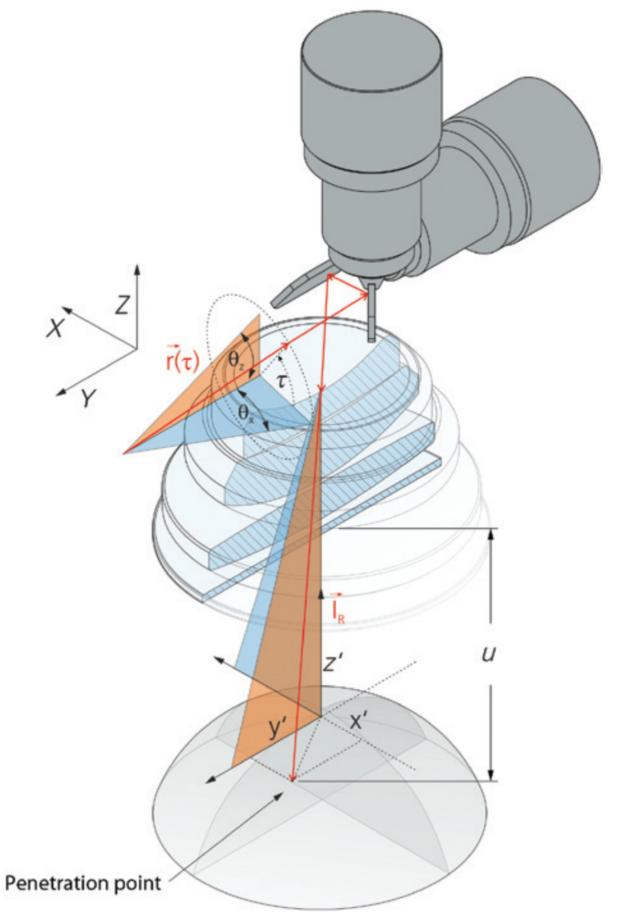

Figure 3: Propagation of an individual ray through the galvanometer scanner and the F-theta lens. The penetration point emerges if the ray hits the working geometry (i.e. a sphere).

$$D_{Ry}(\beta)=\begin{bmatrix}\cos\left(-2\beta+\frac{\pi}{2}\right) & 0 & \sin\left(-2\beta+\frac{\pi}{2}\right)\\ 0 & 1 & 0\\ -\sin\left(-2\beta+\frac{\pi}{2}\right) & 0 & \cos\left(-2\beta+\frac{\pi}{2}\right)\end{bmatrix},$$

where α and β designate the mechanical scan angles. The coordinates of the penetration points on the surface are calculated with

$$\begin{bmatrix}x'\\ y'\\ z'\end{bmatrix}=\begin{bmatrix}u\cdot\cos^{-1}I_{Rz}\cdot\cos\left(\tan^{-1}\frac{I_{Ry}}{I_{Rx}}\right)\\ u\cdot\cos^{-1}I_{Rz}\cdot\sin\left(\tan^{-1}\frac{I_{Ry}}{I_{Rx}}\right)\\ u\end{bmatrix},$$

where u designates the distance between the F-theta lens and the penetration point in z-direction and is analytically calculated by substituting $[x', y', z']$ in surface functions that mathematically describe the working geometry [8]. Alternatively, u is interpolated numerically in the case of more complex surfaces that are provided, i.e. by CAD-data. An amount of intersection points is gathered by resubstitution of $u(\tau)$; $\tau=[0, 2\pi]$. The intersection curve emerges from the interconnection of these points.

Calculations for several working geometries (spheres, cylinders) yield that the deformation can be considered as elliptical if the curvature of a continuous shaped working surface is approximately 200 times larger than the spot diameter. In this case, the deformation is characterized by two parameters that describe the ellipticity M_{an} and the rotation γ of the ellipse, and that vary with the working position (Figure 4).

M_{an} and γ are calculated vector-numerically for several working geometries and working positions [9, 10]. Figure 5 exemplarily illustrates the results for a spherical working geometry with a curvature of 185 mm, a focal length of the F-theta lens of 163 mm, a scan field of ~60×60 mm^2 (results from α,β±0.175 rad), and a spot size of 6.52 mm (chosen for

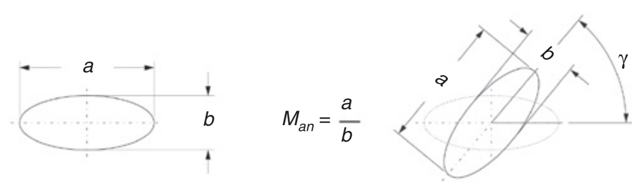

Figure 4: Elliptical characterization of the deformation.

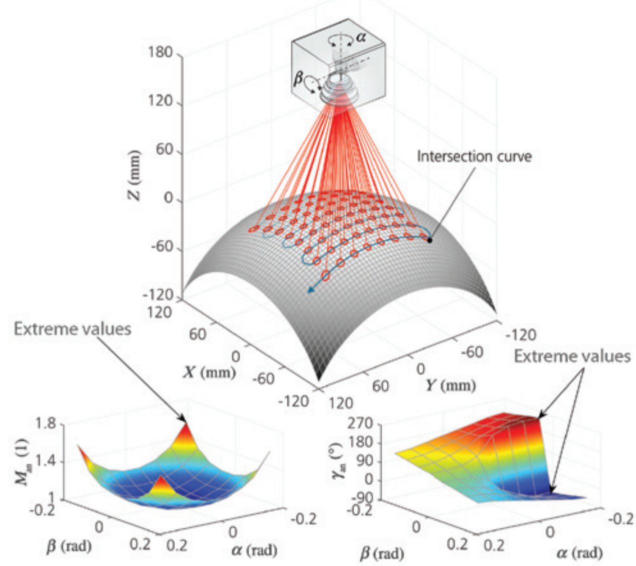

Figure 5: Top: Calculated intersection curves for a spherical working geometry at different working positions. Bottom: Characteristic curves for M_{an} (left) and γ (right).

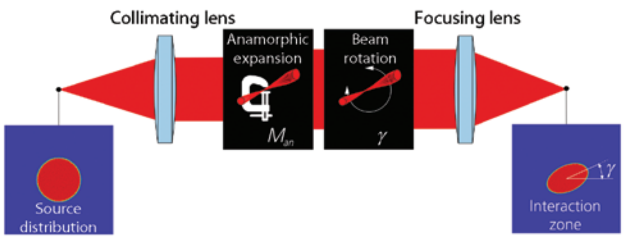

Figure 6: Simplified optical setup for anamorphic beam shaping.

a better visualization, $\theta_{x,z}$=0.02 rad). The top of the picture depicts the intersection curves at different working positions. In the lower left- and right-hand side, the calculated M_{an} and γ are plotted against the scan angles. The characteristic curves exhibit extreme values. These offer information about the maximum deformation that has to be compensated by the further discussed active optical system.

2.2 Active optical system design

If an anamorphically shaped laser beam is focused on a tilted working surface, it subsequently becomes circular again. Therefore, on continuous shaped working geometries, the variant elliptical deformation is compensated by variable anamorphic beam shaping, whereas the degree is directly proportional to the parameters from Figure 6.

The optical setup to realize the beam shaping is strongly simplified as depicted in Figure 7. A fiber coupled laser source is firstly collimated and then focused in the interaction zone. The size of the spot diameter depends on both the focal length of the focusing lens and the diameter of the collimated beam. Hence, the beam shaping is realized by two active optical devices that anamorphically expand and rotate the collimated beam and that are arranged directly in front of the focusing lens.

The following requirements are postulated for the active beam-shaping devices:

– Anamorphic, continuous beam expansion of the laser beam
– Continuous rotation of the anamorphically expanded laser beam

Figure 7 depicts the detailed beam path of the optical system using the example of a fiber coupled multimode laser source. The anamorphic expansion is realized

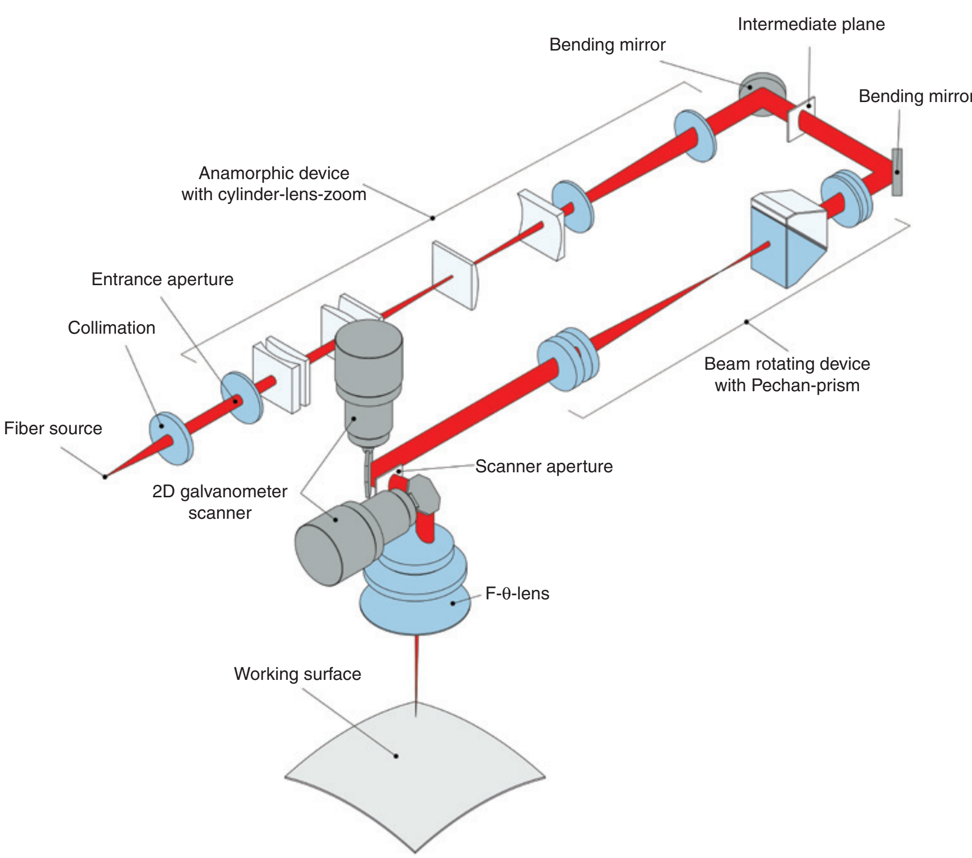

Figure 7: Beam path of the active optical system.

with a cylinder lens zoom telescope, the beam rotates with a Pechan-prism. To avoid the obscuration that arises from residual divergence of the collimated multimode laser beam, both devices exhibit intermediate focusing of the entrance aperture in the aperture of the scanning unit.

The anamorphic device is realized as a mechanically compensated cylinder lens zoom telescope (Figure 8). It comprises nine spherical and cylindrical lens elements and enables an anamorphic expansion of the beam with a magnification in *y*-direction, M_y=2.2.

Figure 9 depicts the realized zoom telescope. To ensure highly dynamic anamorphic beam expansion (~10 Hz), linear direct drives are integrated.

The beam rotation device is realized using a reflection prism. As a Dove-prism would refract the convergent beam at its entrance and exit faces, and would therefore result in astigmatism [11], a Pechan-prism is utilized instead (Figure 10). To maintain the internal total reflection and to withstand laser powers up to several kilowatts, it is made out of sapphire. The birefringence can be minimized by choosing an appropriate orientation of the crystal axis of both parts of which the prism consists. The beam is rotated twice as much as the Pechan-prism is mechanically rotated [6].

Figure 11 depicts the realized beam-rotating device. The laser beam propagates through a hollow-shaft direct drive motor (torque motor). It enables high dynamic

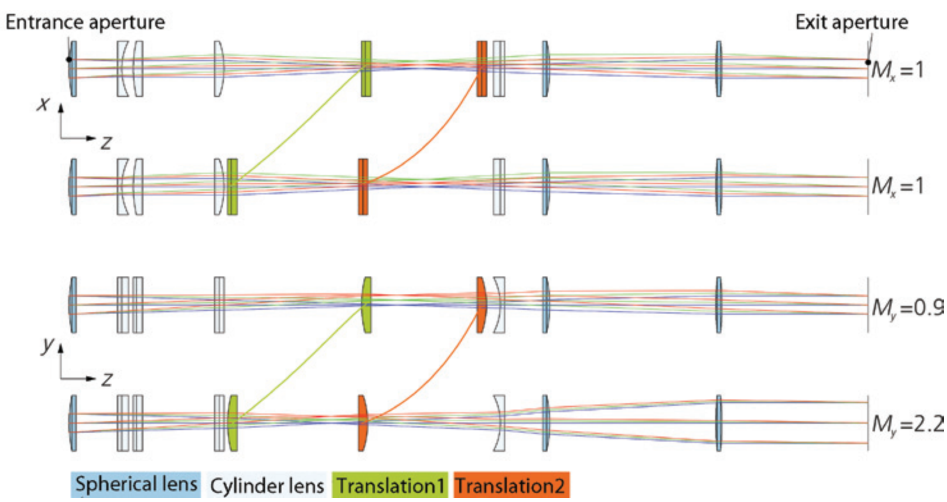

Figure 8: Beam path of the cylinder lens zoom telescope.

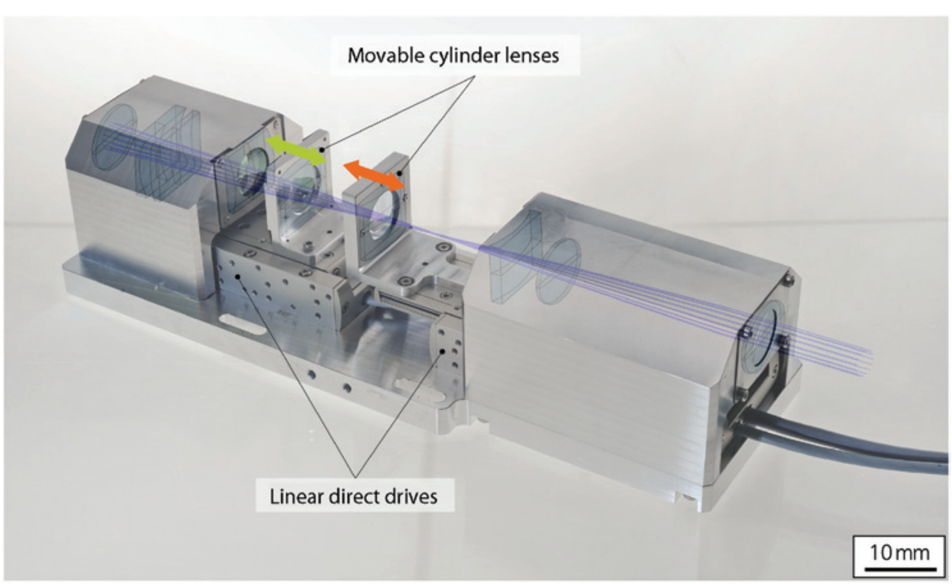

Figure 9: Mechanical design of the cylinder lens zoom telescope. Linear direct drives from Jenny Science AG, Rain, Switzerland.

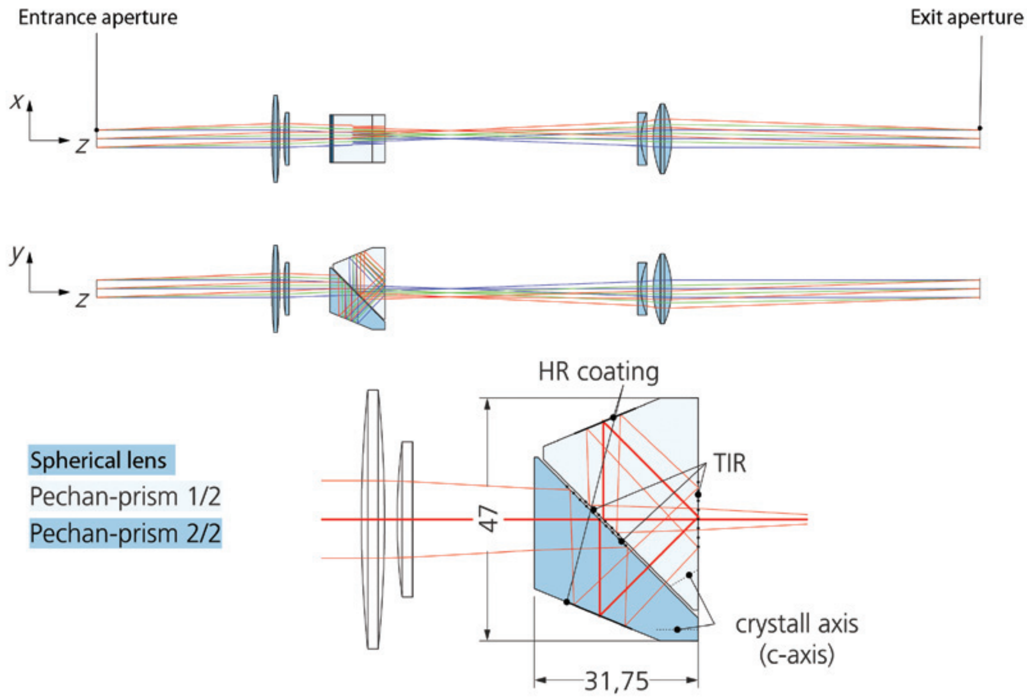

Figure 10: Beam path of the beam-rotating device.

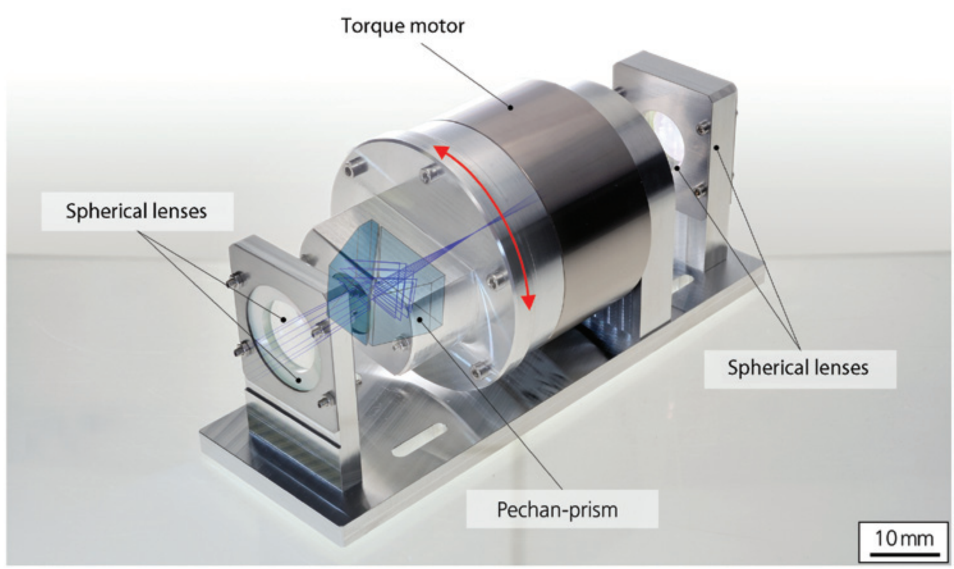

Figure 11: Mechanical design of the beam-rotating device. Torque motor from NSK Deutschland GmbH, Ratingen, Germany.

rotation (~10 Hz) of the Pechan-prism and therefore a quick rotation of the anamorphically expanded laser beam.

3 Control design

The elliptical deformation changes with the working position, and the amount of beam shaping therefore has to be synchronized with the scanning unit. A closed-loop control is very difficult to realize as the integration of a measurement device to acquire the deformation is very challenging. Therefore, an open-loop control approach is pursued, which is based on a model-based prediction of the deformation under predetermined working positions (Figure 12).

The technology processor is of utmost importance as it firstly determines the actual working position by reading

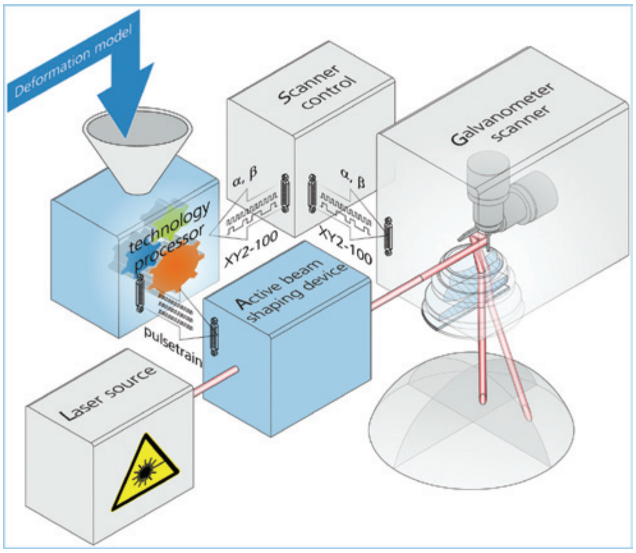

Figure 12: Schematic depiction of the open-loop control approach.

out the scan angles α and β from the digital protocol (XY2-100) between the scanner control and the galvanometer scanner. A mathematical model enables the calculation of the elliptical deformation as a function of the working position, and as the required beam shaping is proportional to the deformation, the technology processor is able to inversely determine the amount of anamorphic beam expansion and beam rotation. Subsequently, pulse train signals are generated that control the linear and rotation stages within the optical devices.

As this open-loop control approach necessitates strong determinism and short iteration times (t<10 µs), the algorithms have to be executed very quickly. The utilization of reconfigurable hardware (FPGA) enables the execution of the three relevant routines within iteration times <6 µs (Figure 13). This is sufficient for a high-speed synchronization of beam shaping and beam deflection.

4 Results

The adaptive optical system has been realized for the 3D surface structuring by laser remelting [6, 9, 10]. Figure 14 depicts the laboratory setup of the overall optical system.

The cylinder lens zoom telescope and the beam-rotating device are integrated directly in front of the scanning unit. A scientific study of the impact of the compensation of the structuring quality is the object of current work.

A first verification has been conducted by a simulation of the optical setup. The ray-tracing program ZEMAX enables the simulation of the focal spot on a spherical working geometry (same parameter as in Figure 5). Figure 15 depicts the qualitative simulation results within three working positions.

The top row depicts intensity distributions that are elliptically deformed and rotated. The degree of deformation depends on the working position. After applying anamorphic beam shaping (bottom row), the intensity distributions become almost circular. Minimal residual deviations from an ideal circular shape arise from the defocusing of the marginal rays in the border area.

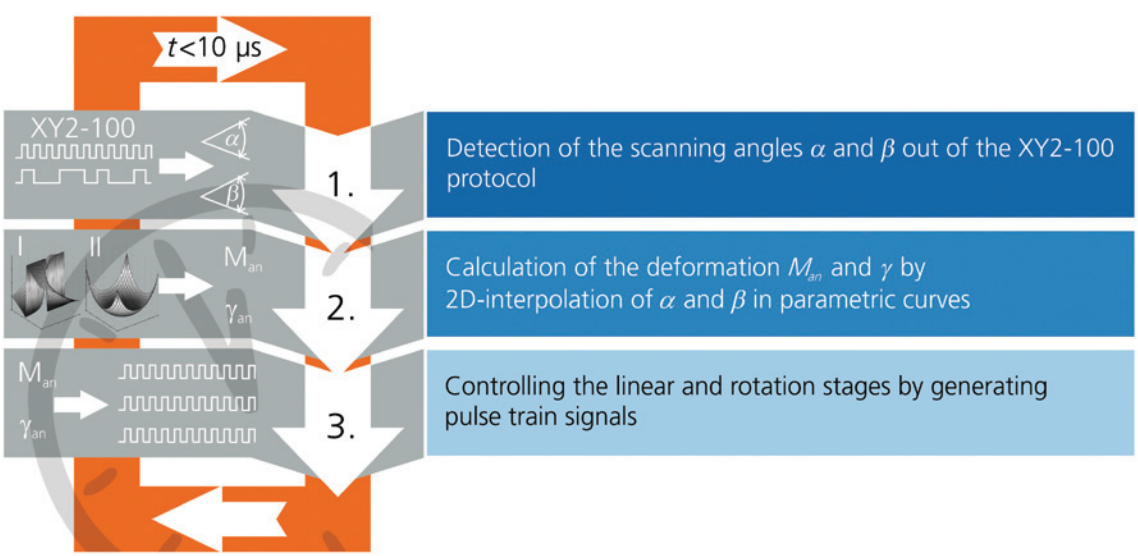

Figure 13: Software routines of the technology processor executed on FPGA hardware.

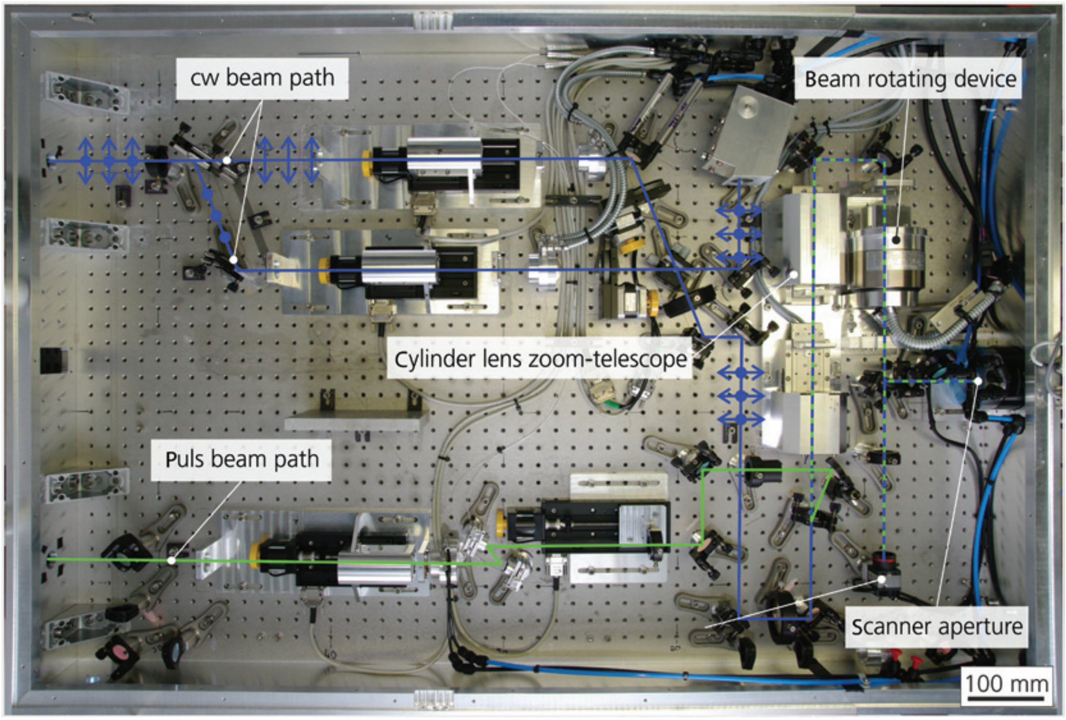

Figure 14: Laboratory setup of the optical system for 3D surface structuring by laser remelting.

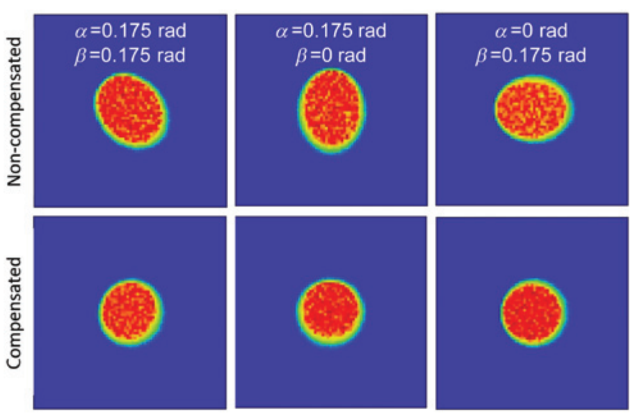

Figure 15: Simulated intensity distributions on a spherical surface before (top) and after (bottom) applying anamorphic beam shaping.

5 Conclusion

An adaptive optical system has been developed that enables the compensation of projection-induced focus deformation for scanner-based applications in laser materials processing. If the focused laser beam hits a 3D working surface, the focus spot is approximately elliptically deformed, whereas the degree of deformation varies with the working position and the surface geometry. This is compensated by integrating additional optical devices between the laser source and the scanning unit. These devices allow for a continuous anamorphic expansion and rotation of the laser beam, and enable an invariant circular focus spot in the interaction zone. Currently, the approach is limited to continuous surfaces. As, for example, jumps and steps would result in non-elliptical deformation, it cannot be compensated by the discussed beam-shaping system.

The synchronization of beam shaping and beam deflection is realized with an open-loop approach. Further improvement is achieved by the utilization of a closed-loop control circuit, as both the working geometry and the working position do not have to be considered during control. To take full advantage of this alternative approach, a measurement device such as a camera is required that accounts for high-speed detection of the intensity distribution in the interaction zone.

The system has been built for 3D surface structuring by laser remelting, and is currently verified. The results will be published in the very near future. The general approach is demonstrated first by qualitative simulation results of intensity distributions.

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