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Process controller for scanning laser surface machining on cylinder surfaces

Jan Düsing[a*], Jürgen Koch[a], Oliver Suttmann[a], Stefan Kaierle[a], Ludger Overmeyer[a]

[a]*Laser Zentrum Hannover e.V., Hollerithallee 8, 30419 Hannover, Germany*

Abstract

Laser beam scanners are often combined with a mechanical axis stage in order to take advantage of both the high dynamics of the scanner device as well as the motion flexibility of the stage system. However, synchronization is yet a challenging control task because of diverging operation principles and incompatible operation frequencies. In this study we investigate a laser process control strategy for laser surface machining which is implemented on a field-programmable gate array (FPGA) data processor. The control system reads geometrical data from memory, performs real-time coordinate transformations based on current stage position sensor signals and generates control signals for the laser scanner and beam modulator. The system is able to solve all computation tasks with an update rate well beyond 100kHz and thus allows for processing strategies which involve continuous motion of scanner and rotation axis for seamless circumferential laser processing on cylindrical surfaces.

Keywords: laser micro machining; surface processing; real-time process controller; FPGA

1. Introduction

The gaining interest in ultrashort laser pulses as a tool for surface machining applications such as surface texturing, thin film processing or surface functionalization resulted in a major technological progress in the development and industrial application of ultrashort pulsed laser sources. Nowadays, laser sources with average power beyond the 100-W range and pulse repetition rates in the MHz range are commercially available [Hönninger and Akhil, 2016; Russbueldt et al. 2009]. Accompanied with this development the

* Corresponding author. Tel.: +49-511-2788-276; fax: +49-511-2788-100
E-mail address: j.duesing@lzh.de

optical systems for beam handling and control system must be able to follow the trend toward larger processing rates. An ultrafast laser beam with pulse repetition rates in the kHz to MHz is typically deflected by dynamic beam deflectors such as galvanometers, polygon scanners, or acousto-optical scanners [Römer and Bechtold, 2014; Zimmermann et al. 2015].

In order to address large area applications, the deflector systems are combined with a mechanical stage system for workpiece positioning which enlarges the accessible surface area. However, the highly dynamic optical systems of laser machines are not easily integrated into the numerical control (NC) architecture of a conventional stage system. A typical NC processor generates control signals up to the one or two-digit kHz range, depending on the number of axes to be synchronized and the motion complexity. This is by far below the dynamic capabilities and requirements of optical deflectors and modulators, e.g. galvanometer scanners typically operate at 100 kHz signals, and acousto-optical or electro-optical modulators offers response times in the MHz range. Thus, development of control systems which can operate the high dynamic optical system while maintaining synchronized motion to the NC stage is challenging and demands for novel solutions.

In this work we investigated a control architecture which is capable to fully synchronize the motion of a galvanometer scanner to the motion of a rotation stage on the surface of a cylinder workpiece. The control system is implemented on a field-programmable gate array (FPGA) chip which allows for installing parallel data processing structures. In the following we present the principle idea of operation and the implementation on a FPGA chip. Finally, the synchronization capability of the controller is evaluated experimentally and it is shown that motion synchronization well into the 100 mm/s range is possible

2. System Architecture and Principle of Operation

Generally, execution of laser scanning tasks on a circumferential surface of a cylindrical workpiece requires some kind of motion of the workpiece with respect to a laser scanner since the field of view of the scanner never covers the entire surface in a fixed orientation of the workpiece. In a conventional approach a scan task is split into segments which are executed in a predefined sequence (NC program) through a move-and-scan procedure. This procedure ensures that the motion of the stage system has halted while processing the scan job in order to maintain high positioning accuracy. However, this approach induces jerk and vibrations into the machine frame during the acceleration phases and also results in unproductive secondary time while the stage system is moving to the next position.

To reduce secondary times during laser processing it is desirable to continuously move the workpiece in a smooth motion while keeping the laser scanner busy all the time. This requires at least two mechanisms of synchronization: (1) starting and executing scan tasks within the scanner field and possibly decide which task shall be executed next if more than one task is in view of the scanner, and (2) synchronizing the motion of the workpiece with the scanner at a high update rate to make use of the full dynamics of the scanner system.

The architecture of the controller developed in this work is based on the idea of planning, generating and synchronizing scan path signals in real time based on input signals from encoder position sensors and the current state of the laser machine. Thus, the control system interfaces close to the machine components and directly drives the signals for laser pulse triggering, scanner and acousto-optical modulator, as shown in Fig. 1. The NC-controller is used in this experiment only to set the stage system into motion. Synchronization of scanner and workpiece motion is entirely based on position encoder signals of the servo motors.

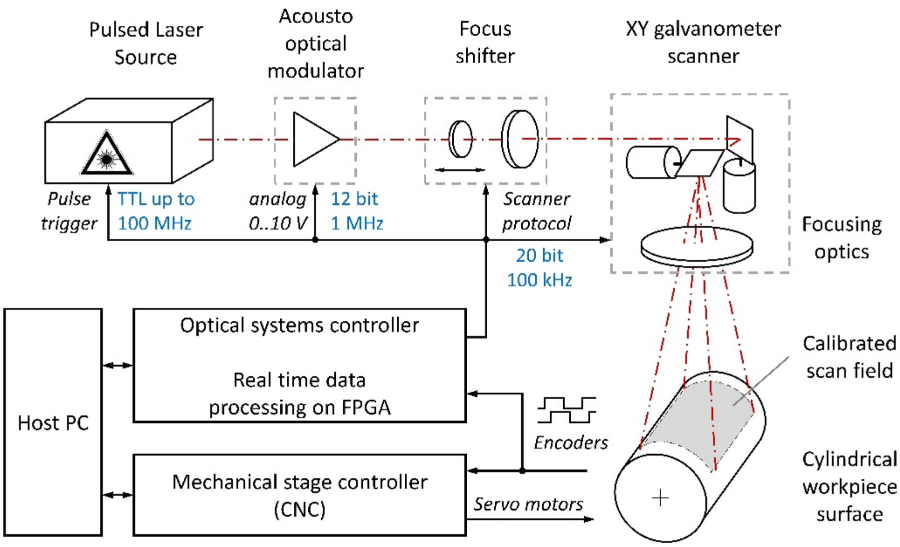

Fig. 1. Fast digital computations are performed on the optical system controller. It reads the current stage position and generates signals for laser source, modulator and galvanometer scanner.

The data flow graph of the logical functions on the optical system controller forms to main feedback loops, as depicted in Fig. 2. These two feedback loops address both synchronization requirements, scan job scheduling on a slower time scale and exact scanner positioning during workpiece motion at high update rates, respectively. During the process preparation micro scan jobs are generated by splitting up the laser task into small fractions. Each micro scan job shall thereby fit into the scan field considering that the field is moving during processing. The amount of geometrical data associated to each micro job is not strictly defined, but might consists of a single point, a line segment, a polyline, or a collection of several geometrical objects. A micro scan job may hold additional data such as laser intensity, scan velocity or pulse frequency. Furthermore, each micro job is associated with a trigger condition. Once the condition of a micro scan job is met the scheduler commands the path generator to execute the micro scan job. The output of the scan path generator is a stream of coordinates in a global model coordinate system at high data rates (e.g. 100 kHz for galvanometer scanner control). Within the scope of this work the dataset composing a micro scan job in listed in Tab. 1.

Table 1. A micro scan job is composed of scheduling and geometric data sets

Data set	Description
Scheduling condition	• Encoder trigger position • Execution counter • Priority of execution
Geometry data	List of polylines, each vertex holding: • Surface scanning speed • Laser beam intensity • Coordinates

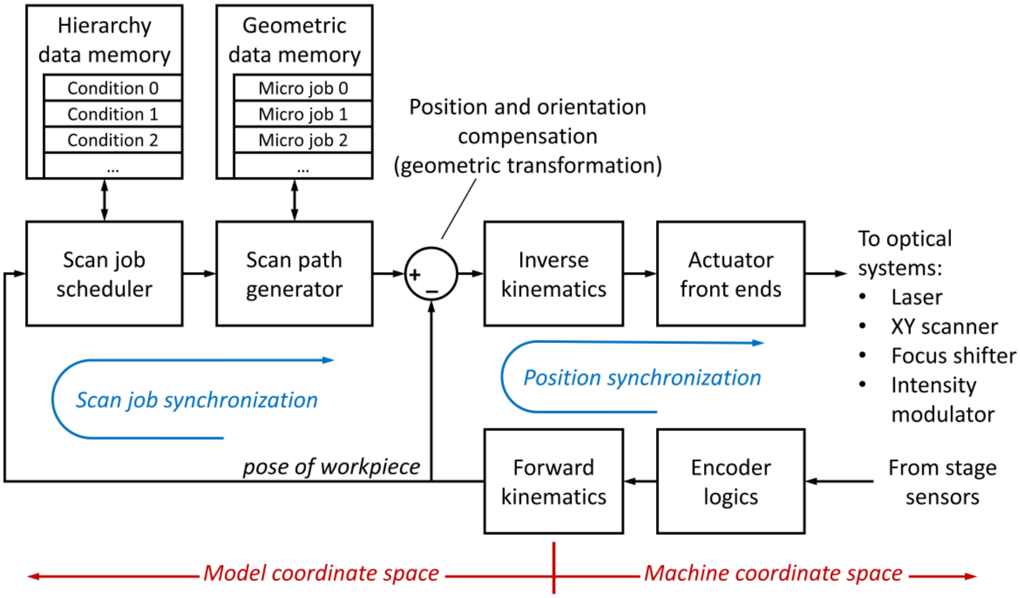

Fig. 2. The data flow graph of the optical systems controller implements two synchronization feedback loop: position synchronization on a fast time scale and scan job synchronization at a less critical time scale.

High positioning accuracy is established through the positioning feedback loop (cf. Fig. 2). The axis encoder coordinates are transformed by forward kinematic functions into the model coordinate system. The result – the orientation of the workpiece in model coordinates – is then vectorially subtracted from the stream of scanning coordinates in order to move the micro job into the view of the scanner field. A set of inverse kinematic transformation functions transform these coordinates into actuator coordinates. The actuator frontends finally generate command signals for each optical system of the laser machine. Any latency within this feedback loop adds up and results in delayed signal output and subsequently positioning errors. It is thus eminently important to reduce latency within the positioning feedback loop during the design and implementation, as it will be discussed in the following sections.

3. Hardware Implementation

High data throughput and signal rates are achieved by implementing the system based on the concept of a pipelined data flow processor. In a data flow architecture operations are implemented as logic cells and interconnected along a data flow graph to form a digital signal processing system. This concept stands in contrast to control flow architectures used in central processing units (CPU). CPUs serially executes a set of instructions as defined by an execution program. Program code can easily be changed and allows for very complex control strategies. However, CPUs can also result in bottlenecks in terms of data throughput at large workloads and high signal rates. Since the data flow graph of the optical systems controller (cf. Fig. 2) follows a strict pipeline model it is reasonable to choose the data flow architecture and implement it on a FPGA chip in order to benefit from parallel data path structures and direct data access to external machine components. The processing performance is thus rather limited by dependencies within the data flow graph and available logic resources of the FPGA.

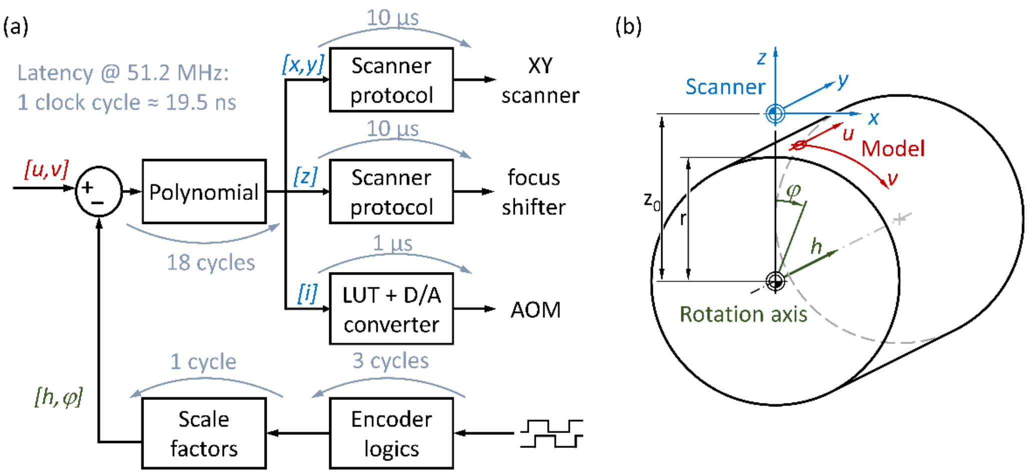

Fig. 3. (a) Implementation of the fast feedback loop for position synchronization. The curved arrows symbolize the latency of each logic core; (b) Definition of the coordinate systems for model, rotational axis and scanner.

The hardware implementation targets an Intel Cyclone IV FPGA chip. The IP cores are written in the hardware description language Verilog and assembled by the Platform Designer software tool as part of the Intel Quartus development suite. Laser process data is downloaded to an external SDRAM memory which provides fast data access during scanner operation. All cores are synchronously clocked by a 51.2 MHz clock signal generated from an on-chip phase-locked loop core. The signal output from the FPGA pins are amplified by appropriate TTL driver, differential line driver, and digital-to-analog converter for transmission to the laser triggering, galvanometer scanner, and acousto-optical modulator, respectively. For the experiments an ultrashort pulsed laser system operating at a wavelength of 1030 nm is directly triggered by the TTL signals and modulated by means of an acousto-optical modulator. The laser beam is deflected by a Scanlab intelliSCAN III 10 galvanometer scanner combined with an Scanlab varioSCANde focus shifter. A telecentric f-theta lens with a focal length of f = 160 mm focuses the laser beam into a volume accessible by the laser scanning of approximately 80x80x20 mm^3. A cylindrical steel surface with a diameter of D = 50 mm is coated with black ink layer so that any area irradiated by the laser beam becomes visible by a strong visual contrast compared to the remaining area. The cylinder is mounted on an Aerotech ADRT rotary stage with an encoder resolution of 14400 lines per revolution (0.025°).

Scanning on a cylindrical surface can be described with two dimensional coordinates under the assumption that the cylinder exactly rotates around its axis, i.e. it is mounted congruent to the rotary stage. Furthermore, if the model coordinate system is also defined in cylinder coordinates the forward kinematic transformation reduces to a linear scaling of the rotation resolution into the resolution of the model space. The inverse kinematic transformation from model space into scanner coordinates is based on polar-to-cartesian equations (refer to Fig. 3b for notations):

$$x = r \cdot \sin(v - \varphi) \tag{1a}$$

$$y = u - h \tag{1b}$$

$$z = r \cdot \cos(b - \varphi) - z_0 \tag{1c}$$

The radius r and distance z_0 of the cylinder surface are assumed to be constant in this work.

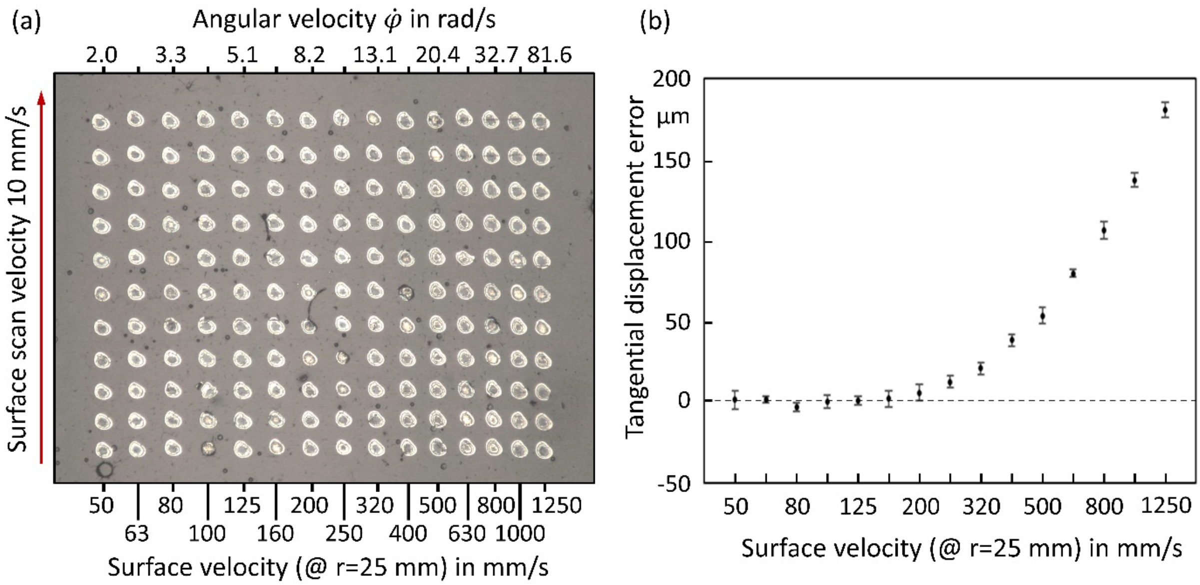

Fig. 4. (a) Evaluation of positioning errors while scanning on the surface of a rotating cylinder. Lines are scanned vertically with high scanning speed (10 m/s @ 100 kHz) to separate single pulses. At high superimposed rotation speed the displacement of the laser pulses becomes visible; (b) The dynamic displacement error as a function of surface velocity. Beyond approx. 200 mm/s the error increases significantly the surface speed.

Additional transfer functions such as lens distortion or misalignment of the optical path introduces additional positioning errors. Therefore, a more general polynomial function is used to approximate the overall optical transfer function. Using polynomial model has the additional advantage that it can be constructed solely by multiplication and summation operations which are mapped on FPGA logics with little effort. The parametrized core solves polynomial functions of fifth degree within 18 clock cycles (approx. 0.35 µs). As indicated in Fig. 3a, worst case latency in the data path is defined by the scanner interface protocol and response times of the galvanometer deflectors. The XY deflectors have a specified lag in the range of 0.1 to 0.2 ms and the focus shifter is assumed to have an even longer response time (not explicitly specified). Thus, the response time of the position feedback loop is mainly defined by the scanner response time and the galvanometer dynamics.

4. Dynamic Positioning Errors

Dynamic positioning errors are induced by a positioning lag due to the response time of the position feedback loop and the galvanometer scanner. In order to visualize the effect of positioning errors during dynamic motion situations a set of lines are scribed on the surface of the steel cylinder. The lines are processed on the moving cylinder with stepwise increasing of the rotation speed. The execution of each line is triggered by an encoder position condition which is defined in the center of the scan field. Fig. 4a shows a microscope image of the laser spots on the cylinder surface. The lines are scanned in axial direction (vertical in Fig. 4a) with a scanning velocity of 10 m/s at a pulse repetition rate of 100 kHz resulting in a spot-to-spot distance of 100 µm. Each line is placed on a 100 µm tangential grid. However, the line distance decreases with increasing angular velocity of the cylinder. The resulting tangential displacement error can be attributed to positioning lag. In Fig. 4b the displacement error is plotted over the tangential surface velocity of the cylinder. It is evident that significant displacement error occurs at surface velocities beyond approx. 200 mm/s. However, operating the rotation stage below this critical surface velocity results in practical negligible displacement error, and thus, allows for fully synchronized laser surface processing on cylindrical workpieces.

5. Conclusion

A motion synchronization of laser scanners with a mechanical stage system can be realized by directly feeding the sensor signals of the position encoders into a fast digital signal processor. Fast position feedback loops and a direct generation of the scanner signals in real time results in short response times and minimized positioning errors. The implementation of the entire system on a field-programmable gate array (FPGA) chips allows for parallel data structures and short processing latencies. The capabilities of system synthesis on FPGA chips shows great potentials for high data rate processing for efficient controlling of fast laser beam machining applications – not only for the control of galvanometer scanners but also for even faster beam modulators and deflectors.

Acknowledgements

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