Advanced Machining and Accessing of Information by means of Gentelligent Micro Patterns

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Summary: An advanced technology for information storage on machined component surfaces by means of micro patterns and optical data read-out is presented. Existing procedures for the cutting of micro patterns during the turning process are substantially extended by introducing two-dimensional data arrays. A closed-loop control system enables the cutting of patterns depending on the rotation angle of the workpiece and therefore on the spatial relationship between the cutting edge and the surface. To allow the flexible use of this technology, no additional angular transducer is employed, but the internal angular signal of the machine tool control is utilised. It is demonstrated that established control methods such as phase-locked loops provide sufficient accuracy for stabilisation of the angular position estimation. The advantage of two-dimensionally aligned micro patterns is demonstrated in a novel optical data read-out method. In addition to increased data integrity, adapted image processing algorithms allow the reconstruction of the stored data using a single monochrome camera image of the surface. A novel FTS for milling operations is introduced, expanding gentelligent information storage towards face-milled components. The findings are a further step towards the shop floor application of this technology.

Keywords: Actuator, Micromachining, Information, Image Processing

1. Introduction

The Collaborative Research Centre (CRC) 653 explores innovative component properties and concepts for their manufacturing and implementation in production engineering processes. One of the CRC's visions is the inherent storage of significant component information, for example production date or production drawings, on the component itself. Thus, external data repositories or additional storage media become obsolete [1, 2]. The approach stands distinct from commercial technologies, such as barcodes or RFID, due to its focus on an inseparable link of workpiece and information. Unlike other highly sophisticated inherent approaches, for instance cast-embedding technologies [3, 4], the presented technique does not interfere with the existing process chain of a workpiece, nor does it require additional process steps or even machine tools.

Recent work demonstrates that machining of micro patterns into the component's surface during finishing using a Fast Tool Servo (FTS) offers a promising possibility to store digital data [5]. The general idea is to encode the data in a first step into an appropriate representation, e.g. a non-return-to-zero (NRZ) line coding. Following, it is converted to an analogue excitation signal driving an actuated cutting tool, cutting cavities into the surface, representing binary digits. Figure 1 depicts the conversion of digital information to a varying depth of cut which leads to the cutting of defined cavities (Figure 4). It was shown that optical read-out methods using directed illumination can be applied to reconstruct the depth of the machined micro patterns [5]. A modified Hidden Markov Model (HMM) approach followed by a Viterbi-like decoding was chosen to track the edge of the data groove, obtaining the depth and thus the binary digits. In addition to the provision of a persistent memory, an authentication framework to protect components against plagiarism based on distinct, unambiguous surface properties was developed [6].

2. Information storage and retrieval using micro patterns

Based upon previous work [7, 8], the performance of the technology with respect to the turning operation and the read-out process is considerably improved. A major advancement is realised, offering an enhanced process security and promising an increased acceptance in industry.

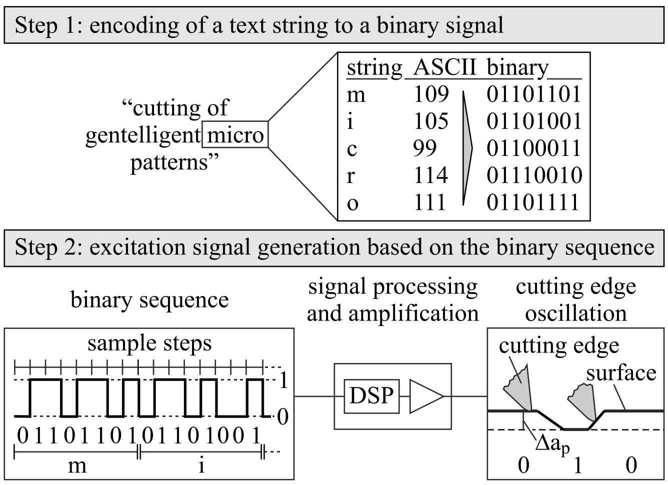

Figure 1. NRZ encoding of textual information.

In a pre-processing step, the serial data bits are re-arranged into two-dimensional arrays of micro patterns, allowing for increased data integrity and simplified read-out algorithms. Hence, the reconstruction of data from a single monochrome image captured by off-the-shelf industrial cameras using directed illumination is feasible. To realise this 2-D alignment, the patterns have to be cut depending on the rotary angle of the workpiece. Therefore, the FTS control is synchronised with the machine tool control. The gentelligent toolchain is depicted in figure 2.

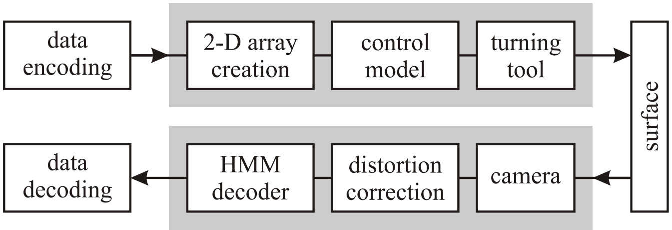

Figure 2. Gentelligent information toolchain.

2.1. Synchronisation of FTS and cutting process

In order to realise two-dimensional micro patterns, it is essential to have real-time knowledge of the precise instantaneous cutting edge position with respect to the surface. To guarantee universal applicability and to avoid the need for additional angular transducers or other sensors, the internal angular signal of the rotational speed control is interfaced. The obtained signal originates from a digital-analogue conversion carried out internally in the machine control. As a result of using rectangular pulses as D/A reconstruction filter, the signal is staircase shaped.

Furthermore, due to strong electromagnetic interferences in the shop floor environment caused by the high-voltage converters of the machine tools and other disturbances, the signal-to-noise ratio of the angular signal is low. In addition, the angular signal exhibits a rather poor time resolution compared to the rotational speed of the machine due to a sampling frequency of approximately 160 Hz. According to Shannon’s sampling theorem, however, band-limited signals such as the phase vector describing the spindle rotation can be perfectly reconstructed if being sampled at a frequency of more than twice the maximum signal frequency, i.e. more than twice the rotational speed [9].

This reconstruction of the noise-free angular values is carried out as follows. First, the sampled angular values as well as the precise sampling points are recovered from the noisy signal. For that purpose, the tapped signal is interpreted as a discrete-time, continuous-valued pulse-amplitude modulation (PAM) signal. Employing a well-established approach from the area of digital communications engineering, the noisy signal is fed to an adaptive matched-filter receiver with phase-locked loop (PLL) guided clock recovery [10]. Second, these recovered, yet still discrete-time angular values are subsequently used as an input to second PLL. This additional stage reconstructs the spindle rotation with sufficient accuracy.

The adaptive matched-filter approach described above results in minimal additional computational cost for the control model and auto-adjusts to a wide range of different angular signals. A residual positioning jitter of $\sigma = 0.12$ relative to the bit length is achieved.

2.2. Single-shot read-out

In order to facilitate fast and robust read-out of the stored information during a later phase in the lifecycle of a gentelligent component, the layout of the written micro patterns follows certain design constraints. Arranging the data into two-dimensional blocks is crucial for data reconstruction from a single image. A rectangular shape is used, simplifying correction of image distortion and tracking and decoding of the data grooves. Furthermore, multiple data blocks can be allocated side by side to increase the overall storage capacity. The camera’s field of view constrains the geometric dimensions of the pattern, whereas the data density is defined by the structuring frequency in relation to the machining parameters. In particular, the number of bits per track is determined by the rotational speed of the component and the groove distance by the feed. A block layout of e.g. 55 tracks containing 16 bits each can be realised, applying productive process parameters. Each block is followed by a guard area of adjustable size containing blank tracks. Thus, data blocks are sufficiently spaced from adjacent blocks to ensure reliable separation. Furthermore, each block is preceded by a synchronisation header consisting of a distinctive bit pattern which is repeated several times.

Together with the block boundary mark, these synchronisation words assist the following process of image distortion correction. Generally, the performance of a data receiver deteriorates if the transmission channel is non-stationary and exhibits a drift, i.e. if the tracks grooves in the captured image are not parallel. In particular, the Hidden Markov Model (HMM) read-out approach relies on parallel grooves. Camera images, however, are uncalibrated, resulting in non-parallel track grooves. Notably, they frequently exhibit geometric distortions caused by perspective as well as lens imperfections such as radial distortion. Furthermore, images have no particular a-priori orientation. In a first step, a coarse translational and rotational alignment is therefore carried out with the help of the newly introduced synchronisation words and block boundary marks using phase-correlation based template matching.

Following, the image distortions are determined by exploiting the strong spectral image content along the feed direction caused by the equidistant groove marks. Using this prior knowledge, the necessary correction can be estimated in the frequency domain. For this, the dominant local frequency and phase is found for each position within the surface data block by performing a windowed Discrete Fourier Transform. A two-dimensional phase unwrapping followed by a smoothing operation is then carried out to obtain an estimation of the deviation from the undistorted image. These estimates are now used to build an adjusted non-uniform sampling grid and to interpolate a rectified image. This image is partitioned into separate parallel grooves which are subsequently passed to the HMM edge tracking and decoding stage.

Employing this non-parametric automatic correction method using prior information about the image structure, a broad range of low-cost industrial cameras can be used “out-of-the-box” without further calibration or modification. The read-out procedure is significantly sped up compared to previous approaches using a microscope (cf. [5]). Adapting the HMM decoding to the novel image capture and pre-processing toolchain, a raw bit error rate, i.e. without any forward error correction (FEC), of $BER = 2{\cdot}10^{-3}$ is achieved.

3. Cutting micro patterns during face milling operations

To increase the range of applications for inherent data storage using micro patterns, the aforementioned technology is transferred to face milling, which is one of the most common and most versatile machining processes. The high dynamic axial excitation necessary to cut several micro patterns within a single engagement of the cutting edge requires the development of a new FTS for milling operations. By combining a piezo actuator with a central preload a highly dynamic positioning of the end mill in the axial direction with a resonance frequency of $\omega_0 = 4.5$ kHz and a maximum amplitude of $\Delta l_{max} = 30$ µm is realised. A slip ring is used for power transmission into the rotating tool. Strain gauges and a temperature sensor are applied directly to the piezoelectric actuator. Thus, the temperature can be monitored and the structuring depth can be controlled by the strain gauges signal during operation. The constructive realisation of the actuated end mill holder is shown in figure 3.

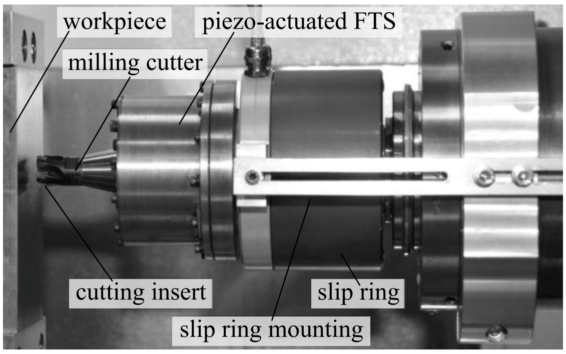

Figure 3. Fast tool servo (FTS) mounted in machine tool.

The actuated milling tool is controlled by a MATLAB-Simulink model processing the binary data sequence along with the rotation angle of the spindle. Thus, the binary signal can be provided depending on the instantaneous cutting edge position on the surface of the component. In order to ensure real-time processing, the control model is executed on a dSpace industrial control computer system. The amplified signal causes a defined oscillation of the piezo actuator hence of the cutting edge. Thus, the depth of cut is varied and the micro patterns are cut into the surface. Figure 4 depicts a micro-patterned surface machined by actuated face milling as well as the surface topography of a single bit recorded via confocal microscopy. The face milling is performed using commercial inserts and applying standard parameters (Table 1).

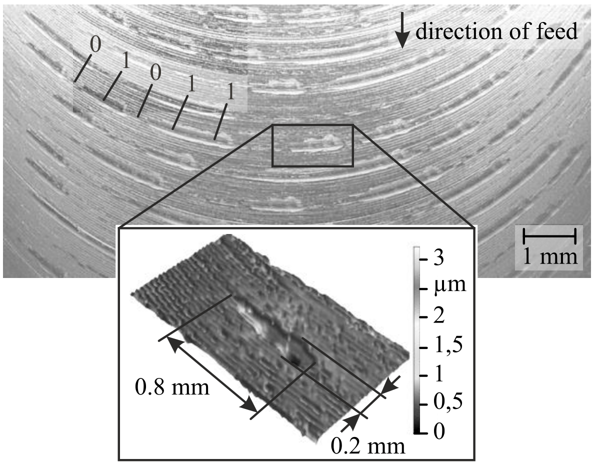

Figure 4. Patterned surface by actuated face milling.

Table 1. Machining parameters of face milling process.

process parameters			
cutting speed	v_c = 300 m/min	feed per tooth f_z	= 0.05 mm
depth of cut	a_p = 0.5 mm	width of cut a_e	= 20 mm
excitation amplitude	a_{str} = 100 V	structuring frequency f_{str}	= 4 kHz

By developing a FTS for milling operations, the field of micro pattern application is extended to face-milled components. Up to 4.000 bit/s can be cut, realising 8 bit/revolution employing productive machining parameters. First results show a data density up to 200 bit/cm² using common cutting geometries. In a next step the cutting edge geometry will be adapted to the kinematics of an actuated milling process. This adjustment has great potential to increase the data density.

5. Summary and Outlook

The presented fast and robust data reconstruction method using a single image of the surface taken by a customary industrial camera provides an excellent basis for future shop floor applications. For that purpose, further research will be carried out developing a portable hand-held read-out unit. Cutting micro patterns in face milling processes is realised using a novel Fast Tool Servo for milling operations, enabling gentelligent information storage in an additional manufacturing process. Future work will include the increase of the data density by implementing forward error-correction schemes, specifically adapted modulation and modified cutting edge geometries.

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