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H4.SMR/452-55

ADRIATICO CONFERENCE ON FOURIER OPTICS AND HOLOGRAPHY

6 - 9 March 1990

ANALOGUE OPTICAL CORRELATION AND ITS APPLICATION

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ANALOGUE OPTICAL CORRELATION

AND ITS APPLICATION

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- MOTIVATION
- COMPUTING WITH OPTICAL ELEMENTS
- COHERENT OPTICAL CORRELATOR
- APPLICATION IN QUALITY CONTROL
- SOME PROBLEMS AND SOLUTIONS

G. Indebetouw
J. Steffen (LASAG)
F. Laeri
B. Schneeberger

CORRELATION

Comparison of functions
- 1-dimensional
- 2-dimensional
- 3-dimensional

Reading Machines
Pattern Recognition
Quality Control
Measuring Techniques
etc.

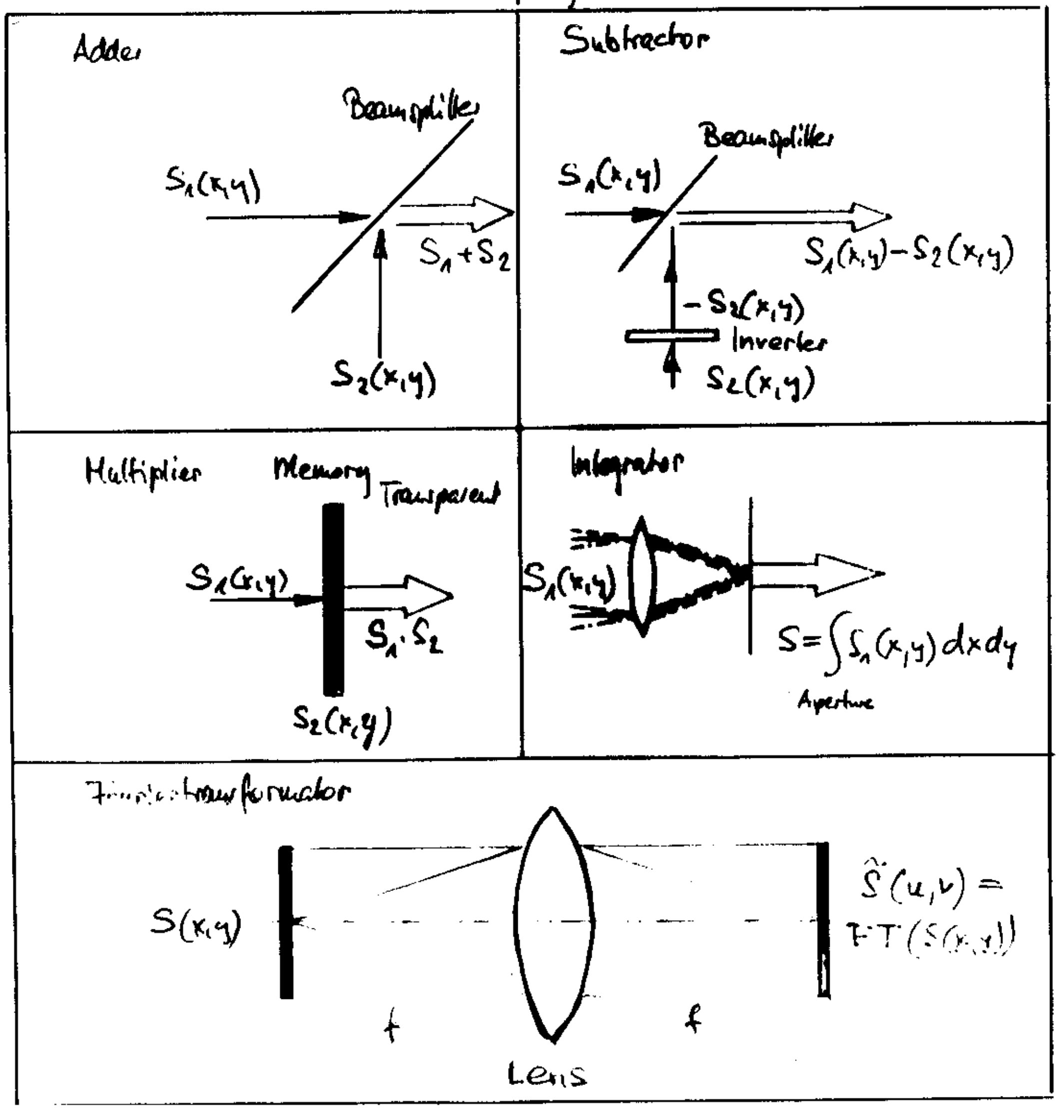
$$f(x,y) \circledast g(x,y) = \iint f(x',y')\, g(x'-x, y'-y)\, dx'dy'$$

$$= \iint F(u,v)\, G(u,v)\, e^{2i(ux+vy)}\, du\, dv$$

Global decision: yes / no
within some tolerances

ANALOGUE OPTICAL COMPUTING

- simple elements for basic operations
- operational oriented language



Operational oriented language

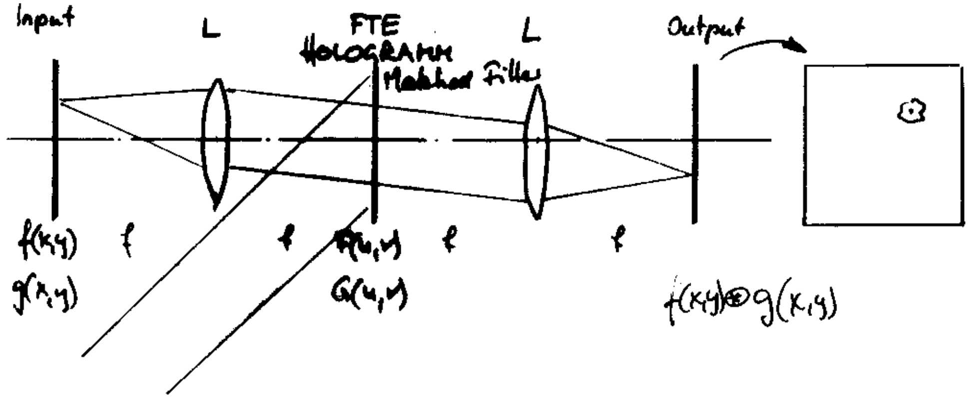
$$M_T = M_n \cdot M_{n-1} \cdot \ldots \; M_2 \cdot M_1$$

Exp. Correlation

$$f(x,y) \circledast g(x,y) = \iint F(u,v) \cdot G(u,v)\, e^{2i(ux+vy)}\, du\, dv$$

$$F(u,v) = FT\{f(x,y)\}$$
$$G(u,v) = FT\{g(x,y)\}$$

Functional oriented language



SPATIAL LIGHT MODULATORS

TABLE 1. AVAILABLE SPATIAL LIGHT MODULATORS

- Electrooptic Spatial Light Modulators (PROM, PRIZ, MSLM, e-Beam DKDP, Photo-DKDP, TIR)
- Liquid Crystal Light Valves (CdS, ZnS, Si, $Bi_{12}SiO_{20}$, Hybrid Twisted Nematic, CCD-Addressed, Variable Grating Mode, Multiple Period)
- Deformable Mirror Devices (Oil Film, e-Beam DMD, CCD-DMD, Photo-DMD)
- Magnetooptic Spatial Light Modulators (Integrated Magnetooptic Arrays, Curie Point)
- Photochromic Spatial Light Modulators
- Electroabsorptive Spatial Light Modulators (GaAs CCD)
- Photorefractive Spatial Light Modulators (PICOC, Volume Holographic Optical Elements)
- Photodichroic Spatial Light Modulators
- Acoustooptic Spatial Light Modulators

TABLE 5. SPATIAL LIGHT MODULATOR MATERIALS

• Electrooptic	• Magnetooptic
• Acoustooptic	• Piezooptic
• Liquid Crystals	• Def. Membranes
• Photochromic	• Photodichroic
• Electroabsorptive	• Photoconductors

TABLE 6. HYBRID SPATIAL LIGHT MODULATORS

- Total Internal Reflection (TIR) SLM
- CCD-Addressed Deformable Membrane Device
- Silicon-PLZT Spatial Light Modulator
- GaAs-CCD Electroabsorptive SLM
- CCD-Addressed Liquid Crystal Light Valve

Reprinted from **APPLIED OPTICS**, Vol. 17, page 911, March 1978

Optical processing techniques in the quality control of micromechanics

G. Indebetouw, T. Tschudi, and J. Steffen

Coherent optical processing methods have been investigated for the real time recognition and control of mass-produced pieces in automatic machining and assembling lines. In particular, an optical correlator is proposed in which the information of a master piece is stored in a hologram. Problems such as the optimization and generation of the hologram, the detection of particular defects, the adaptation of the response curve to the practically given tolerances, and the reliability have been investigated, and prototypes of control systems have been realized.

I. Introduction

Actual technologies in mass production need workpieces and components of an extremely high reliability. Automatic machining and assembling lines ask therefore for 100% nondestructuve testing and for piece recognition methods working in real time.

Figure 1 shows schematically an automatic production and assembly line, where different pieces are manufactured and assembled. The control system supervises the production, selects bad pieces, and rejects them from the process. To guarantee a continuous operation of the assembly line, an intermediate storage is required, where the position of the pieces is usually lost. Therefore, the control system can in addition be used as a sensor to detect the position and orientation of the pieces in order to grip and mount them correctly. Some requirements of an automatic mass production for the control system are

(1) noncontact testing,
(2) testing rates corresponding to piece production rates,
(3) real-time evaluation,
(4) piece positioning requirements realizable with existing handling equipment,
(5) reliable operation in industrial environment,
(6) control costs in reasonable relation to production costs.

Most conventional nondestructive testing methods are either visual systems or image scanning and recognition systems. These methods are however slow compared to the usual production rates and allow only a statistical control.

Therefore, optical comparison techniques have been studied and tested. The coherent optical correlation method was found to be able to perform a 100% control in real time and to fulfill in many cases the above mentioned requirements.

The coherent optical correlator is well known in optical information processing.[1] Figure 2 shows such an optical correlator which was applied to piece control. The spectrum (Fourier transform) of the test piece is compared with the spectrum of the master piece which is stored in the hologram. The dotted beam path was used to generate the hologram. The optics C generates a second Fourier transformation so the detector produces a signal proportional to the correlation of the two object transmission functions. This signal is maximum if the test piece is identical with the master piece and decreases if any defect exists. Such a system gives a global signal on all the defects. The main interest in the coherent optical method is its high processing speed, a major requirement for a real-time control system linked to automatic production and assembly lines. Practical applicability of this method required the investigation of the following points:

(1) the resolution of the method (smallest recognizable deviation), which should be in the practical range of 0.1% to a few % of the piece dimension;
(2) the response curve (correlation signal vs deviation of the test pieces from the master piece), which has to be adapted to the given tolerance;
(3) the recognition of different characteristics with different individual tolerances;
(4) the piece positioning requirements, which have

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Received 11 July 1977.
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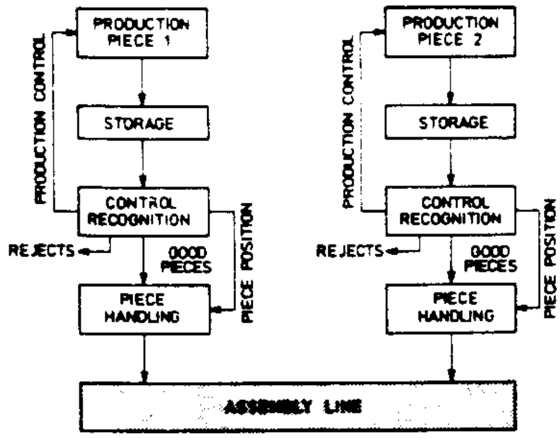


Fig. 1. Control and recognition system in an automatic piece production and assembly line. The piece production is supervised, and the piece position is detected to grip and handle the pieces correctly.

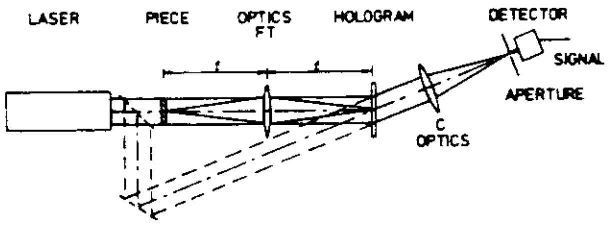


Fig. 2. Coherent optical correlator (type A) used for piece control in transmission. Dotted reference beam path used to take hologram of a master piece.

to be compatible with existing piece handling equipment;

(5) the reproducible fabrication of the hologram;

(6) the reliability and limits of the method which must fulfill industrial standards.

II. Optical Correlation for NDT

A. Position and Orientation of the Pieces

The influence of the position and orientation of the test pieces on the correlation signal is known;[1,2] within reasonable limits the correlator is translation invariant. A translation of the piece affects only the position of the correlation signal but not its magnitude.[3] Detection with position independent detectors (vidicons, diode arrays, CCD, etc.) or by beam scanning means decreases the positioning requirements of the pieces. Figure 3 shows the same correlator as Fig. 2 but with a beam deflector to scan the detector area (type B). If the pieces are supplied continuously, a one-directional scanner with direction perpendicular to the piece movement is used. For stepwise supplied pieces a two-directional scanner is needed. If the pieces cannot be positioned angularly (dented wheels, nonsymmetric pieces), a spinning image rotating prism can be used (Fig. 4). Figure 5 shows the correlation signal vs the piece position x for a rectangular piece of 1-mm width measured with the system of Fig. 3.[4] Curve (a) demonstrates the necessity of positioning the pieces within ± 10 μm $[(\Delta s)/s \leq 0.05]$. This requirement was reduced to ± 0.3 mm [curve (b)] by using a scanner. The scan angle and the related scan frequency can be adapted to the position tolerance of the pieces. The two scanning means (types B and C) can be combined if the pieces are not positioned translationally or angularly.

These scanning means give the additional possibility of detecting the piece position by using the scanner position at the moment of maximum signal (correlation signal). This feature can be used in an automatic assembly line to grip and handle the pieces correctly.

B. Response Curve

To be able to separate rejects from the production line according to given tolerances, the response curve (correlation signal vs deviation of the test piece from the master piece) has to be adapted to the tolerances. The response curve can be influenced by the transfer function of the hologram and the pupil aperture of the

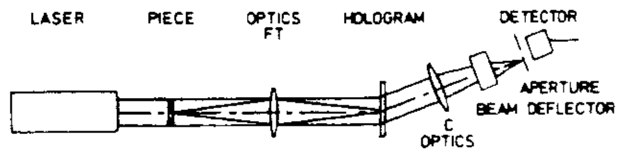


Fig. 3. Coherent optical correlator (type B) with beam deflector used if pieces cannot be positioned accurately.

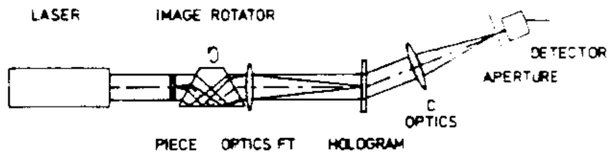


Fig. 4. Coherent optical correlator (type C) with image rotator used if pieces cannot be orientated accurately.

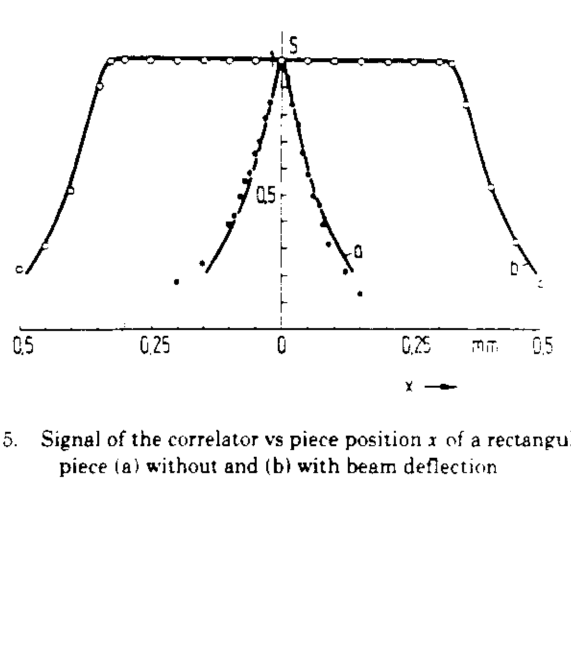
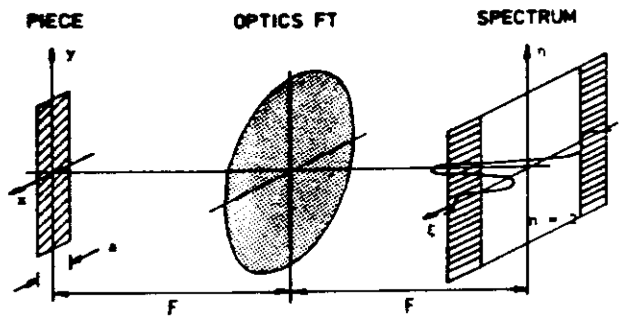


Fig. 5. Signal of the correlator vs piece position x of a rectangular piece (a) without and (b) with beam deflection.



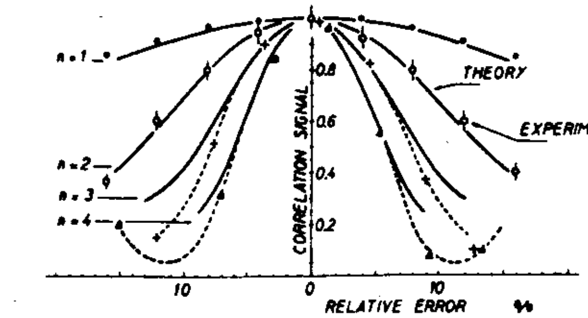


Fig. 6. Adaptation of the response curve to the required tolerances by varying the spectral bandwidth.

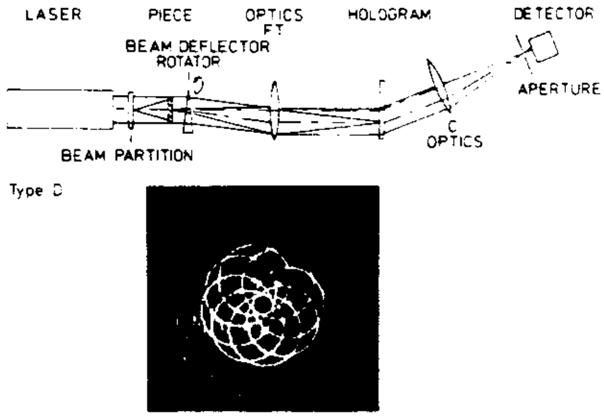


Fig. 7. Coherent optical correlator (type D) with beam partition and beam deflector/rotator used to control several individual features of the piece separately; eight-channel hologram.

complete system.[4] Figure 6 demonstrates the influence of the spatial bandwidth of the hologram on the response curve for a rectangular piece (theoretical and experimental values). The hologram can therefore be matched to the searched signal and optimized for the best possible evaluation of a particular feature. In some cases it was necessary to use adequate additional masks in the piece or in the spectral plane in order to select the desired features.[5]

C. Information Selection

If several features of a piece have to be evaluated separately, or if features with different individual tolerances exist on the same piece, it is necessary to separate the information about these features on the hologram. Figure 7 demonstrates an arrangement (type D), which was used to separate different information about the piece. The holograms matched to each different feature were taken by beam partition and were arranged on the photographic plate on a circle by a rotatable prism (beam deflector, rotator). Figure 7 shows in addition a photo of an eight-channel hologram of a piece. For the control operation the rotating prism allowed a check of the features sequentially with one detector. The number of different features is limited by the cross talk (cross correlation of one feature with the filter of another feature).

III. Optimization and Realization of the Hologram

The essential point of the described correlators is the hologram, more precisely the possibility of generating the desired response curves with the maximum SNR. Photographic hologram manufacturing is the most direct and easy way, but it is limited by the dynamic range of the photographic emulsions. Figure 8 shows a photographically produced hologram of a rectangular piece with three holes, where the position deviation ϵ of the central hole had to be controlled. The hologram recording parameters which are most readily available—the exposure and the ratio of reference to object beam—were adjusted experimentally in order to get the

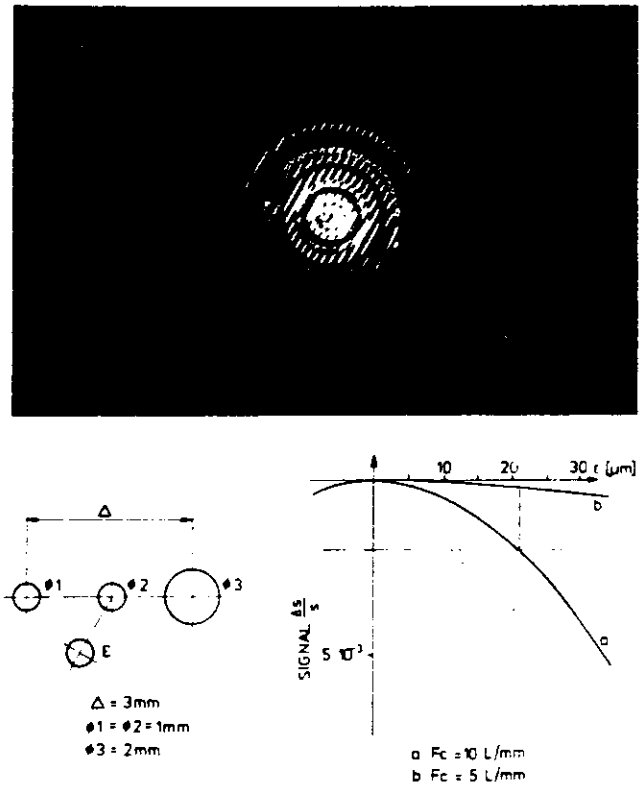


Fig. 8. Photographically recorded hologram of a piece with three holes and relative correlation signal $(\Delta s)/s$ vs deviation of position ϵ of central hole.

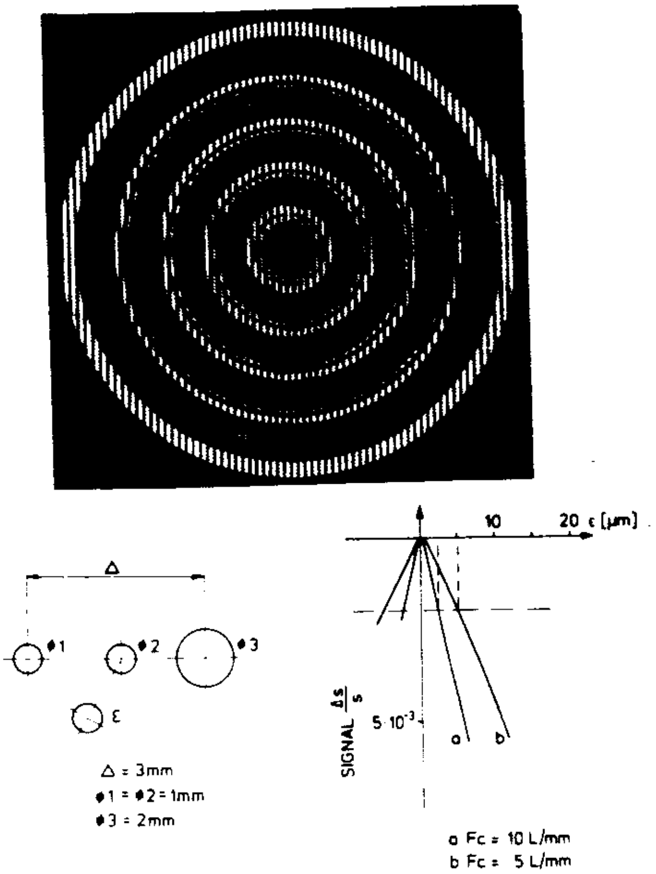


Fig. 9. Synthetically generated hologram of the piece with three holes and relative correlation signal $(\Delta s)/s$ vs deviation of position ϵ of central hole.

maximum sensitivity for the detection of the described defect ϵ. The hologram was recorded by overexposing the low spatial frequencies. Two response curves were measured for cutoff frequencies of 5 and 10 lines/mm. At a relative signal variation of 2×10^{-3}, a deviation $\epsilon = 20\ \mu m$, corresponding approximately to a position error of 0.5% of the piece dimension, could be resolved. To check the possibility of getting higher resolutions, a computer aided (synthetic) hologram manufacturing method was investigated. Figure 9 shows a synthetic hologram of the three-hole piece in Fig. 8. The information from the piece was computed and plotted by the computer in binary form, then reduced optically and etched in a Cr layer (amplitude hologram) or in a quartz layer (phase hologram).[6] The binary form was found to be a good compromise between high sensitivity and attenuation of scattered noise for the practical problems investigated. Synthetic holograms were found to be especially adequate to adapt the response curve to the detection and measurement of a particular defect and to enhance critical parts of the workpiece. Often, only a few important features on a piece are important and must be controlled without influence from all other features which may have larger mechanical tolerances as, for example, the diameters of the holes in the piece in Fig. 8. The hologram can be optimized to minimize the effect of the unimportant features on the response curve.[7] Figure 9 shows in addition two response curves calculated for cutoff frequencies of 5 and 10 lines/mm. Compared with the corresponding photographic hologram, a position deviation of $\epsilon = 2\ \mu m$ (5×10^{-4} relative error) could be measured at the same relative signal variation of 2×10^{-3}. The computer manufacturing of

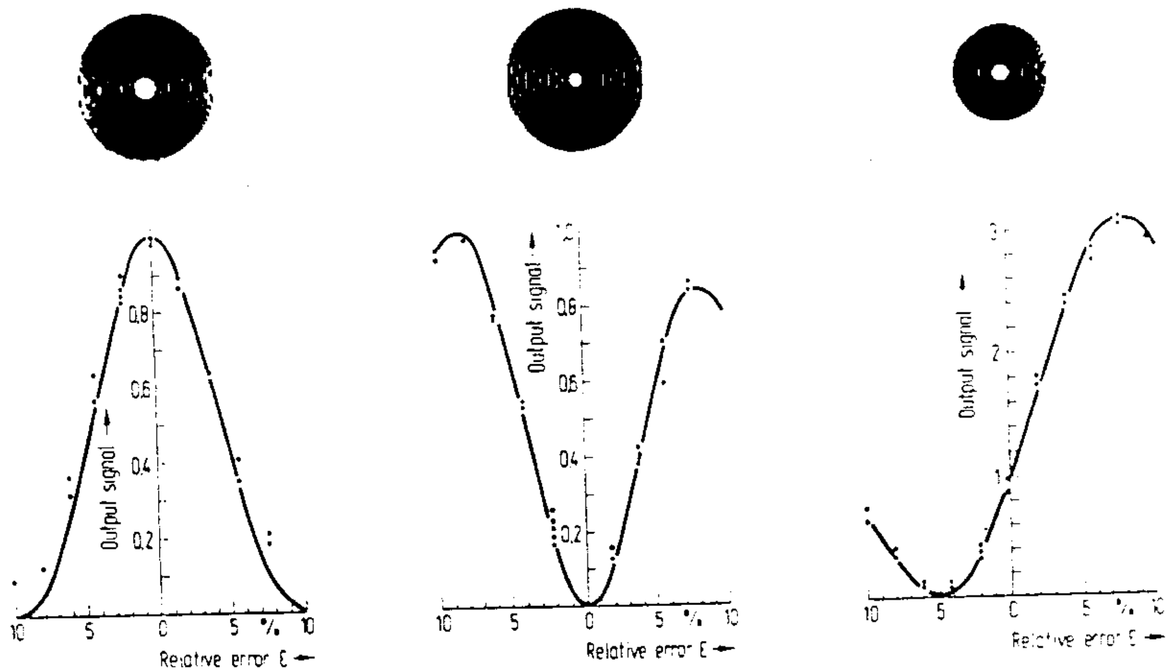


Fig. 10. Three synthetic holograms of a piece with a circular hole (ϕ = 1 mm) with a phase shift to obtain different types of response curves.

the hologram offers in addition the possibility of influencing the shape of the response curve by phase change. Figure 10 shows three synthetic holograms and the corresponding response curves for a piece with one hole of 1-mm diam. The linear response curve has the practical advantage of being able to detect the sign of the deviation as well as its size.[8]

IV. System Concepts for Automatic Quality Control

An essential limitation on the coherent optical correlation is its inability to use the light scattered on the irregular (rough) surface of many mechanical pieces. In many practical cases the surface state of the pieces to be controlled was uncritical; only the shape (contours) of the piece was essential. Control of such metallic pieces in reflection was therefore limited or even impossible using these methods, which are sensitive to the surface state as well as to the shape deviation.

The coherent optical correlation methods proved successful, however, for the high speed control of mass-produced pieces in transmission, where a large amount of information (complicated contours) had to be handled simultaneously. The reliability of the methods, measured as the probability of recognizing a good piece as a bad one and vice versa, depends on the SNR.[8] Noise sources are, e.g., diffused light from piece edges and from dust, mechanical vibrations, and electrical noise. The control duration or rate depends on the type of piece supply (continuous or stepwise feeding) and on the position accuracy of the pieces (requiring a scanning or not). With a continuous piece supply at a given speed, the control rate is in addition dependent on the piece size. Figure 11 gives some typical data of control rates for a continuous piece supply and of control durations for a stepwise supply. A piece of 5-mm diam and a tolerance of ± 5 μm was assumed.

Several control problems for small mechanical pieces have been investigated with a prototype equipment, realized, and tested in an industrial environment. The pieces are moved continuously on a turntable across the control position. The resolution of the system vs control rate, the stability criteria, and the reliability were investigated. Very strict stability conditions (mechanical and electrical) are required in order to detect small errors ($\simeq$0.1%) reproducibly. If those conditions cannot be fulfilled practically, the described scanning methods can be used to measure the same signal repetitively over a long time. Electronic processing and averaging can then, at the price of a lower control rate, eliminate most statistical fluctuations.

System - Type Piece Position	Control Rate continuous supply	Control Duration stepwise supply
A (x,y) $\leq \pm 5$ μm (θ) $\leq \pm 2\cdot 10^{-3}$ rad	$\geq$ 10 pieces/sec	$\approx$ μs
B (x,y) $= \pm 0.1$ mm (θ) $\leq \pm 2\cdot 10^{-3}$ rad	$\approx$ 1 piece/sec (x-scanning 1kHz)	$\approx$ 20 ms (x,y-scanning 1 kHz)
C (x,y) $\leq \pm 5$ μm (θ) arbitrary	$\approx$ 1 piece/sec (θ-scanning 1 kHz)	$\approx$ 1 ms (θ-scanning 1 kHz)
D (x,y) $\leq \pm 5$ μm (θ) $\leq \pm 2\cdot 10^{-3}$ rad 5-10 indiv. features	$\approx$ 1 piece/sec (θ-scanning 1 kHz)	$\approx$ 1 ms (θ-scanning 1 kHz)

Fig. 11. Typical values of control rate (continuous pieces supply) and of control duration (stepwise piece supply) for the four types of correlators mentioned. Piece dimension $\simeq$5 mm; piece tolerance $\simeq$5 μm.

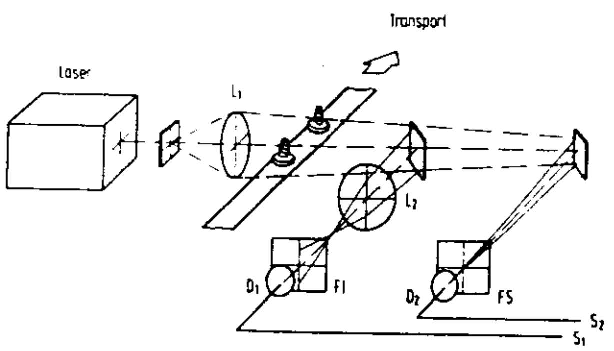


Fig. 12. Systems description of screw testing equipment with one filter FI in the image plane and another FS in the spectral plane. The signals S_1 and S_2 from the detectors D_1 and D_2 are analyzed to evaluate the screw quality.

V. Examples

Applications of the described methods were found in the automatic production and assembly of precision mechanics, the watch industry, the electronic industry, etc., where a 100% control in real time is needed. Some examples are:

Production control: diameter of cylindrical pieces (axis, pins, connectors, screws); diameter of wires and filaments; thickness of foils and ribbons; completeness of punching or tool operation; particle size analysis.

Strength control:[9] welded or soldered wires or ribbons; joint springs or vibrating parts; fatigue tests.

A. Screw Control[10]

One example of a realized system using a simple spatial filtering technique is a screw testing system shown schematically in Fig. 12. Defective screws or screws out of dimensional tolerances had to be sorted out to guarantee a troublefree automatic assembly. The screws are supplied continuously on a transport band. To check the diameter, the profile and the pitch of the screws, the correlation signal S_2 with a simple binary spatial mask FS is evaluated. To check the length of the screws (with much larger tolerances) a coded mask FI in the image plane is used. The two signals are evaluated to decide whether a piece is good or bad. Figure 13 shows the relation between the characteristics of the screw and of its spectrum. The developed laboratory equipment allowed a control rate of $\geq$10 pieces/sec which was only limited by the screw's feeding system.

B. Particle Size Analysis[11]

The measurement of particle size distributions involves the counting and size assessment of a large number of particles. Particle sizing is important in the manufacturing of cements, ceramics, paint, ink, and lacquer and in the evaluation of sprays and aerosols. Optical correlation offers a rapid and accurate particle sizing method. A multichannel system for particles with diameters from 0.5 μm up to 10 μm was developed and is shown schematically in Fig. 14. It is based on the correlation between the far-field pattern of the light scattered by the particles and the calculated scattered light distribution of a master particle which is stored in a synthetic binary hologram. The illuminating laser beam is concentrated by a Fresnel lens simultaneously in three tubes wherein the particles flow at a speed of $\simeq$ 1 cm/sec. Figure 15 shows three response curves of the hologram matched to the 1-μm particles; the parameter is the numerical aperture of the correlation optics.

VI. Conclusions

The practical application of coherent optical correlation methods for piece recognition and quality control in micromechanics was investigated and found to be useful for many problems of automatization in mass production. The practical requirements on tolerances, control speed, reliability, and control costs could be met in many cases. For relatively simple pieces, a resolution of 0.5% could be achieved with a photographically recorded hologram. With optimized synthetic holograms, resolutions of 0.05% are possible. The main technical difficulties and limitations of the coherent optical correlator for its application to quality control of micromechanics have been mentioned and evaluated.

Compared with conventional optical NDT methods based on the scanning of the object or of its image, the coherent optical correlator recognizes and checks the object globally and gives a signal measuring the over-all deviation from a master. The high information content in the hologram can be modified by masks to adapt the response curve to the practical requirements of tolerance. The electronic evaluation is easy and rapid and allows for a real-time evaluation at high control rates.

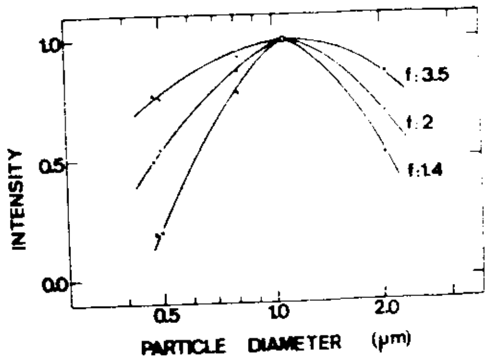


Fig. 15. Response curve of the synthetic hologram of the 1-μm size particle for three apertures of the correlation optics.

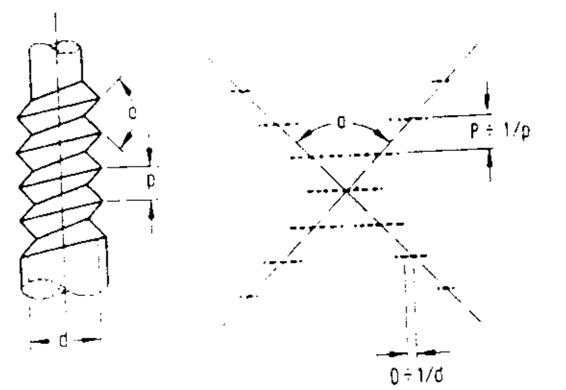


Fig. 13. Characteristics of a screw and its spectrum.

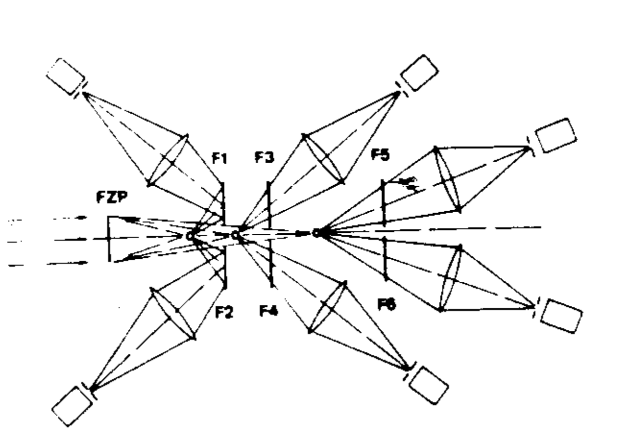


Fig. 14. Systems description of a particle size analyzer using six synthetic holograms F_1, F_2 (in reflection) and $F_3 - F_6$ (in transmission) adapted to particle sizes of 1, 2, 3, 4, 6, and 8 μm. The laser beam is concentrated with a cylindrical Fresnel lens (FZP) on the three tubes wherein the particles flow at a speed of ~1 cm/sec.

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