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Optical 3-D Measurement Techniques - a Survey

ABSTRACT

Close range photogrammetry will be more frequently applied in industry for 3-D-sensing when real time processing can be applied. Computer vision, machine vision, robot vision are in fact synonymous with real time photogrammetry.

This overview paper concentrates on optical methods for 3-D-measurements. Incoherent and coherent methods for 3-D-sensing will be presented. Particular emphasis is put on high precision 3-D-measurements. Some of the work of our laboratory will be reported.

1. INTRODUCTION

The binocular human stereo vision is based on triangulation. Other depth-sensing mechanisms found in nature are based on sonar sensory organs used by bats for in flight range-finding. It is difficult to compete with nature such as with our visual system on the stereo vision but it is useful to learn from it.

Photogrammetry has undergone far-reaching changes in recent years. Modern microchip and digital sensor technology have led to a fundamental revision of the photogrammetric process in the recording, processing, data storage and administration phases. Digital cameras provide for the possibility to process the data practically simultaneously with the recording of the image. In real time processing the time of a process is within one video cycle, which is 1/30 sec or 1/25 sec depending on the video standard /1,2/.

3-D-measurement techniques have great growth potential for industrial applications such as in robotics, in automated manufacturing as well as in microelectronics /1-5/.

Different optical measuring techniques with some applications will be discussed. It is, however, always a compromise between resolution and measuring range.

2. OPTICAL 3-D-SENSING METHODS

Far-reaching changes occurred in photogrammetry and automatic fringe analysis in the last years. Major break-throughs occurred in microelectronic and semiconductor technology. A market of continous interest to photogrammetrists has been close range application in industry. New names have emerged for those applications namely: Robot vision, Machine Vision or Computer Vision. According to Hobrought /1/ "real time" means to assign a z-value (depth) for every pixel within a 17 msec cycle, which corresponds to the integration time of a CCD sensor.

In optical 3-D-sensing the following major techniques can be distinguished.

INCOHERENT TECHNIQUES:

- Triangulation
- Structured light illumination, Moiré techniques
- Image-plane locating systems
- Line of sight ranging, time of flight measurement, phase measurement

COHERENT TECHNIQUES:

- Homodyne Methods
  - Interferometry, Holography
  - Moiré techniques
  - Speckle based techniques
- Heterodyne methods
  - single wavelength heterodyne interferometry
  - multiple wavelength heterodyne interferometry

3. INCOHERENT TECHNIQUES FOR 3-D-MEASUREMENTS
TIME OF FLIGHT AND PHASE MEASUREMENTS

Pulse-echo laser range-finder have long been known as possible approach for distance sensing and 3-D-imaging. In the basic principle a short laser pulse is directed towards to the surface under inspection. The time delay between the transmitted and received pulses is measured to evaluate the range-distance to the target surface at each angular direction. With sub-picosecond pulses from a diode laser as the transmitter source and fiber optic communication detectors high resolution and inexpensive laser range-finder will be available in the future. Submillimeter range resolution seems to be possible in the near future /3,4/. The radar type sensor may be expected to become an efficient tool for robotic applications.

In different laser distance measuring devices the phase measuring technique is applied. A cw-laser is modulated and directed towards the target. The detected signal is compared to the modulation signal to determine the phase shift from which the object range is determined. Due to the relatively low laser energy, integration over several readings is necessary for precise measurements. Submillimeter resolution can be obtained especially when retroreflectors can be used at the target. There are several commercially available geodetic instruments working with modulated radiation of different wavelengths and evaluating the distance to an object by phase measurement. The instruments usually utilize retroreflectors. Some of the manufacturers of commercially available distance measuring instruments are Wild Leitz (D I 2000), Kern (Mekometer) and Zeiss.

TRIANGULATION

Triangulation techniques are very familiar to photogrammetrists, they are conceptually simple. Speed limitation and depth restrictions are severe limitations.

PASSIVE TRIANGULATION

Passive triangulation has long been used in land surveillance and navigation. It is the basis for the well established stereo photogrammetry where the target is observed from two angles. After the recording, the two stereo images are analysed to determine the three dimensional object structure. Computer-processed photogrammetry is a powerful tool in metrology. Although the most popular technique is the stereo approach, other use perspektive, scaling, shading and defocussing in order to extract 3-D-information from one image.

ACTIVE TRIANGULATION

In active triangulation structured light is used in order to illuminate, scan and texture the object by point or line projection, scanning, grid projection and Moiré approach. The use of structured light leads to a high processing speed. Structured light may be used for target generation or may be used in an active oriented sensor.

A basic triangulation set-up is shown in fig. 1. The target is illuminated by a laser and imaged onto a CCD-line or array sensor or position sensitive device. The z position of the laser spot is coded into a corresponding angle Δw respectively a distinct lateral position of the spot image. If one considers the object distance z to be much greater than the triangulation base B, one can estimate the resolution dz by

$$dz \approx \frac{z^2}{B} \Delta w \qquad 1)$$

Triangulation is a very robust method for 3-D-measurements point by point. It is particularly appropriate in a hostile industrial environment.

A scanning triangulation can be very useful to obtain a three-dimensional map of the object surface. A focused laser beam is scanned over the surface to be inspected. The x-y-position of the spot image is known for each deflection angle of the scanning mirrors (galvanometer-scanner). Small differences of the recorded x-y-position with respect to a reference surface allow the evaluation of the distance of the surface from the reference surface. A scanning arrangement is shown in fig. 2, where the computer driven galvano mirrors operates in a scanning mode. More appropriate is the set-up to preselected given points in the object space to be measured. Fig. 3 shows a typical result. Proper signal processing techniques are used to build the three-dimensional computer model from the range information /4,5,8/. The resolution is of the order of 1 mm by a working distance of 1 m. In order to improve the resolution the base B can be extended as shown in fig. 4, where two or more motor theodolites are used. One theodolite can generate the laser pattern to be detected by the second.

MOIRÉ-CONTOUR AND PATTERN PROJECTION TECHNIQUES

The multistripe pattern projection and slanted camera viewing technique for depth ranging can be considered as a comparison of the projected multistripe pattern image with a reference linear pattern which may be recorded by pattern projection on a perfectly plane surface or which may be assumed in advance and inserted as a digital pattern in the camera electronic buffer. The optical equivalent of such an electronic comparison, i. e., the superposition of a multistripe pattern to an actual grid to obtain depth-related optical effects, has long been used for surface contouring before modern image-processing techniques were available.

As in the multistripe projection method, a grid pattern or an interference fringe pattern is projected on the surface to be depth-ranged and is viewed under a different angle by a camera. If the inspected surface is not plane the projected fringes in the image plane are deformed, but they locally match over the image producing depth-related clear or dark areas which are called moiré fringes. Apart from the ambiguity of the direction of height variation, moiré fringes represent contours of equal height.

By tilting one mirror M_1 relative to M_2 (see fig. 5) the period of the projected fringe pattern can be varied. The piezo is used for phase shifting in the fringe analysis. With phase shifting and automatic fringe analysis the ambiquity is overcome leading to a powerful engineering tool for surface topography. Fig. 6 shows a workpiece with contour lines with submillimeter resolution. Moiré techniques with two and more frequencies can be very useful /fig. 5/, because range and sensitivity depends on the grating period /9/.

PATTERN PROJECTION TECHNIQUES

Pattern projection techniques are closely related to the well known "Lichtschnitt" method of Schmaltz triangulation and Moiré techniques. Compared with video imaging methods they provide higher instantaneous intensity and hence better immunity to environmental noise. Serial picture acquisition is mostly used, parallel processing will further be developed. The shape of the recorded light strip provides depth information instantaneously over the full length of the stripes without moving parts. Instead of using periodic multiplestripe pattern, special strip pattern can be generated. Alternatively strip-patterns with different periods can be generated.

IMAGE PLANE LOCATION SYSTEM

Interferometric profilometers are essentially laboratory devices. Inspection in the production is better performed by light scattering techniques or by geometrical optics devices. A device developed in our laboratory is shown in fig. 7 /5,10/. A laser beam is focused on the surface to be inspected by a microscope objective. The laser spot is detected in autocollimation. The light flux passing the pinhole is measured. Maximal signal is detected if the object is in focus for a pinhole diameter corresponding to the diffraction limited laser spot diameter. For a different surface height, the image spot is no longer well-focused on the pinhole, therefore the detected intensity will decrease. By longitudinally oscillating the microscope objective with respect to the surface with a piezoceramic transducer and placing two pinholes symmetrically to the focused spot image, resolutions of the order of 20 nm were obtained. Fig. 7 shows the set up with symmetrically placed pinholes together with a calibration curve. Fig. 8 shows a 3-D-plot of a ceramic surface.

CONFOCAL MICROSCOPY

Confocal microscopy is becoming interesting for high precision topography. In the confocal microscope seen in fig. 9 pinholes are projected on the test surface. For object points exactly in focus most of the light is passing the appropriate pinholes in autocollimation. Bright image spots occur on the video detector. For slightly defocused object portions the larger point images lead to weaker image point contributions when passing through the pinholes. Using a piezoceramic transducer to move the objective the image intensity shows a sharp maximum when passing through the focus. Moving the pinholes laterally the surface profile of an object can be measured. As the objective is moved in axial (z-)direction, the occurring intensity maximal depends on the heights of the object surface. The profile can be observed visually or stored and analysed by using a digital image processing system. Not only the relative variation in height of the object can be obersved by the brightness of the image but also a stereoscopic image is obtained. The data available in the autofocus and range images allows a steroscopic image pair to be generated by computer. Fig. 9 shows schematically our experimental arrangement and Fig. 10 the 3-D-image of a microchip in pseudo 3-D-representation. The resolution was of the order of 20 nm.

4. COHERENT TECHNIQUES FOR 3-D-MEASUREMENTS

Interferometry, holography, speckle and Moiré techniques are becoming useful tools for 3-D-precision measurements in research and for industrial applications. Computer analysis is increasingly important for fringe analysis. Much more information can be extracted from the interferograms, leading to improved sensitivities and accuracies. Therefore automatic fringe analysis and precision phase measuring techniques are very important in applying interferometric techniques.

There are different fringe analysis procedures. They can be classified in static or dynamic techniques /11/. The dynamic techniques are most appropriate. The principle will be described briefly. The superposition of two wavefields $a_1\cos|\omega t - \phi_1(x)|$ and $a_2\cos|\omega t - \phi_2(x)|$ lead to an intensity

$$I(x) = I_o \, |1 + m\cos\phi(x)| \qquad 2$$

where $\phi(x) = \phi_1(x) - \phi_2(x)$, $I_o = |a_1|^2 + |a_2|^2$ and

the contrast $m = \dfrac{2|a_1|\ |a_2|}{|a_1|^2 + |a_2|^2}$.

Because there are three unknowns I_0, m and Φ, three equations or three interferogramms are needed to calculate the unknown phase ϕ. One gets the required number of interferogramms by introducing deliberately two phase shifts of 90 degrees, for instance, before recording the interferogramms. The equations can be solved then and from the phase $\phi = \frac{2\pi}{\lambda}\Delta w$ (Δw is the optical path difference) the relative profile is found. Four and especially five interferogram techniques with four phase shifts of 90 degree are frequently used because ϕ is not so much affected by a phase shifting error /11/.

Fig. 11 shows a modified interference microscope with a high numerical aperture /11/. The phase shifts are introduced by a piezo element into the reference beam. A diode array of 500 x 500 elements was used to study profiles with high resulution. As an example of the fringe analysis a CD-disk is used an object. Fig. 12 shows the topography result of the fringe analysis.

HETERODYNE TECHNIQUES

In interferometry, phase differences of optical fields are transformed into detectable intensity variations. In heterodyne interferometry the time dependent phase variation is analysed in the frequency space. As in equation 2 the two light fields are assumed to be

$$A_1 = a_1 \cos|\omega t + \phi_1(x,y)| \qquad 3)$$

$$A_2 = a_2 \cos|\omega t + \Delta\omega t \pm \phi(x,y,t) + \phi_2(x,y)|$$

where $\Delta\omega = 2\pi\Delta f$ with the frequency shift $\Delta f = f_2 - f_1$ and $\phi(x,y,t)$ is the time varying phase shift leading to a frequency shift by the interference of the two wavefields

$$I(x,y,t) = I_o \left(1 + m(x,y) \cos|\Delta\omega t \pm \phi(x,y,t) + \phi_2(x,y) - \phi_1(x,y)| \right) \qquad 4)$$

The time varying phase

$$\phi(x,y,t) = \frac{2\pi}{\lambda} 2 v t \left(v = \frac{d_z}{d_t} \right)$$

can be determined from the measured Doppler frequency shift δf

$$\delta f = \Delta f \pm \frac{2v}{\lambda} .$$

The profile height

$$\Delta z = \frac{\lambda}{2} \int (\delta f - \Delta f) \, dt, \qquad 5)$$

where Δz is the displacement parallel to the line of sight.

Fig. 13 shows schematically a two beam heterodyne interferometer arrangement. A polarizing beam splitter PBS divides the laser beam with frequency f_1 into the object and the reference beams. The reference is frequency shifted by the acousto-optical modulator AOM. After the beam splitter BS the two beams are recombined and the profile of the scanned object can be obtained by analysing the detector signal i(t) in accordance with equation 5.

Fig. 14 shows a typical result obtained with a similar arrangement used in our institut for microprofile measurements from a mirror-like structure. Resolutions of 1 um laterally and 0.5 nm in depth were obtained by scanning a mirror-like surface. Depth resolutions of 0.1 nm or better were reported at a reduced lateral resolution. Heterodyne techniques are the most promising methods for contactless high-resolution microprofile analysis /10,11/. Other techniques will be developed for robust industrial applications with an extended range.

DUAL WAVELENGTH HETERODYNE INTERFEROMETER

To remove the ambiquity of a single wavelength 2λ techniques can be considered. The principle of a dual-wavelength heterodyne interferometer under study will be briefly indroduced. It should lead to a high resolution range measurement with a resolution of the order of 0,1 mm at a working distance of more than 10 m. Two concepts are under study. The first uses two semiconductor lasers with different wavelength. Fig. 15 shows the principle of the arrangement. In the second concept an AOM is used to generate the two wavelengths.

The principle can be discussed by superposing two heterodyne arrangements, where the two heterodyne signals lead to a signal at the detector

$$i(t) \sim \cos\left(2\pi(\Delta f_1 - \Delta f_2)t - \frac{4\pi}{\Lambda} z\right) \qquad 6)$$

where $\Lambda = \dfrac{\lambda_1\lambda_2}{\lambda_1 - \lambda_2}$ is the resulting wavelength.

5. SUMMARY

Different optical methods can be applied for 3-D-measurements. Extremely high depth resolution can be obtained with coherent and incoherent optical techniques. It is however important to realize that the sensitivity and measuring range has to be considered. Furthermore coherent methods are more sensitive to environmental disturbances than incoherent methods. A lot of progress has been made the last few years. A combination of optical methods with digital image processing seems to be very promising.

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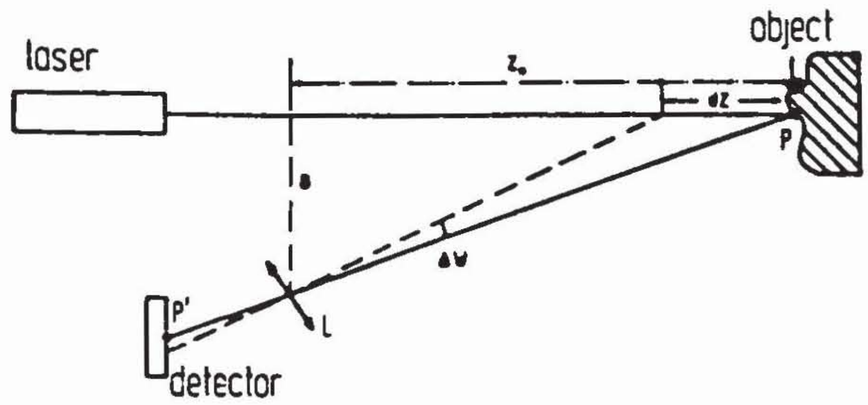

Fig. 1 Basic triangulation set-up

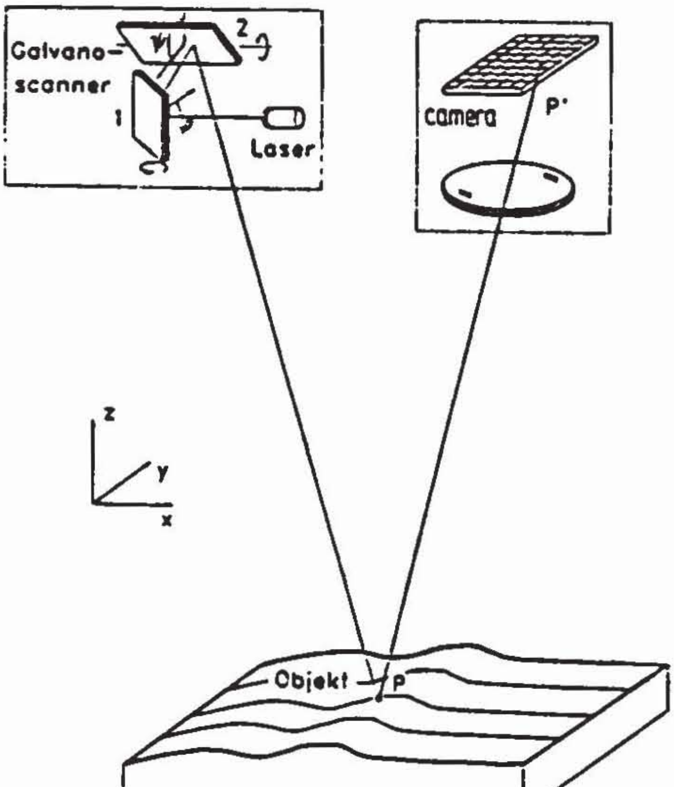

Fig. 2 Scanning triangulation

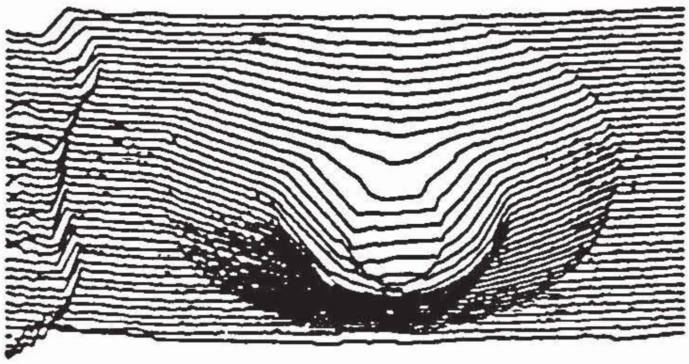

Fig. 3 Result of scanning Triangulation of a cylinder head

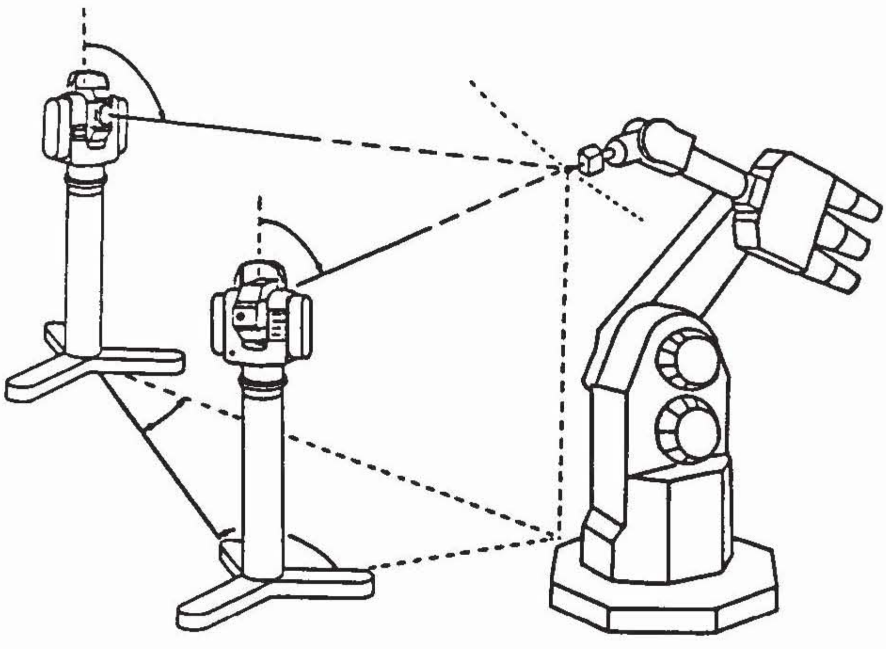

Fig. 4 Triangulation with two motor theodolites (Kern)

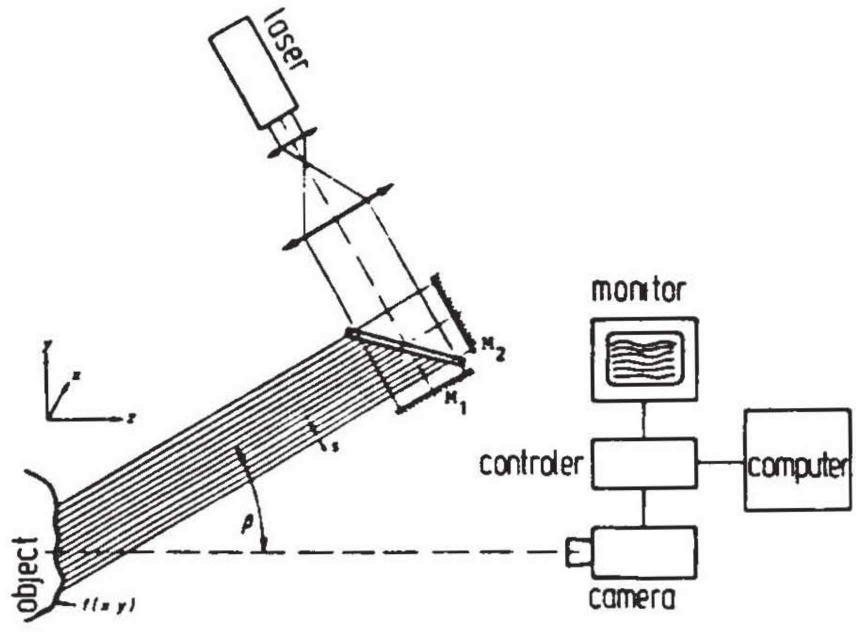

Fig. 5 Projection of interference fringes with variable periods for Moiré topography

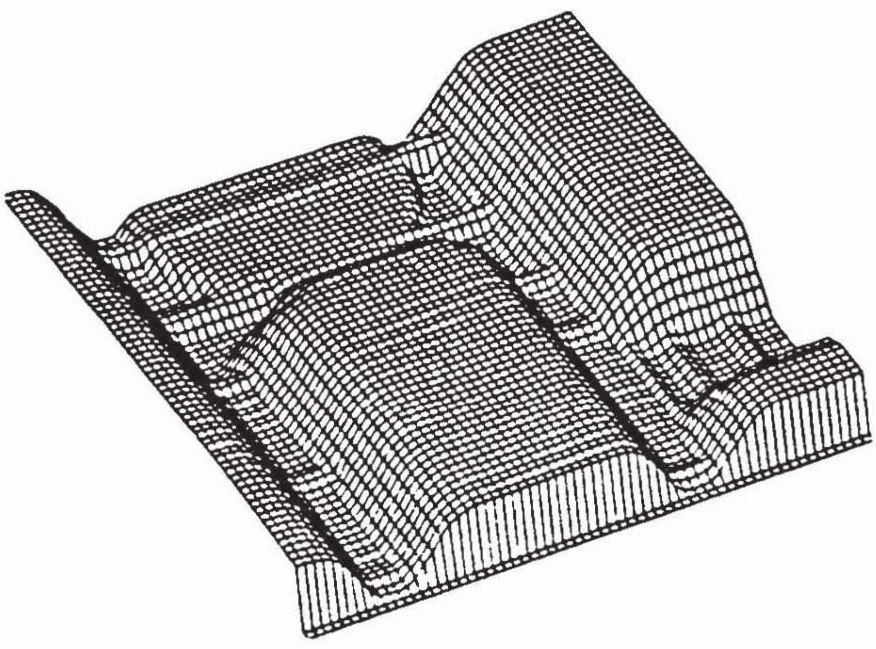

Fig. 6 Experimental result of automatic fringe analysis

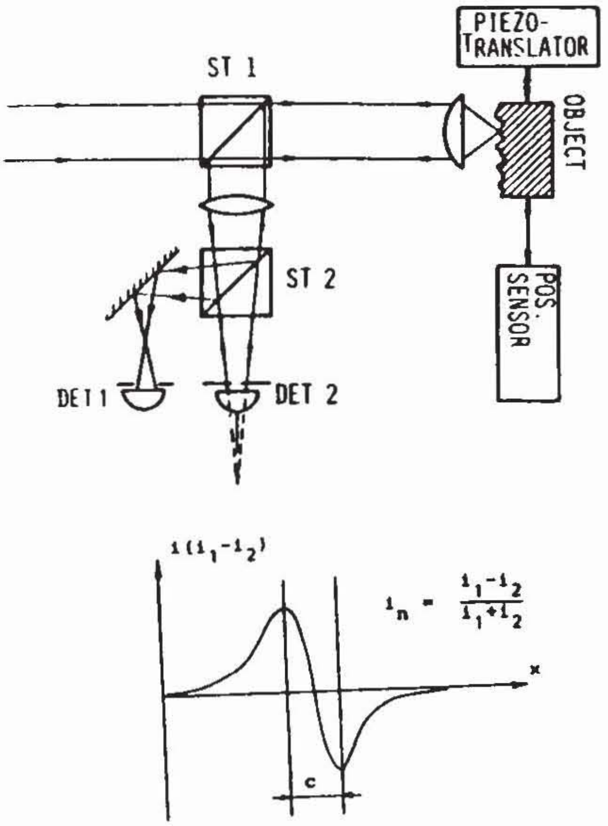

Fig. 7 Principle of image-plane analysis

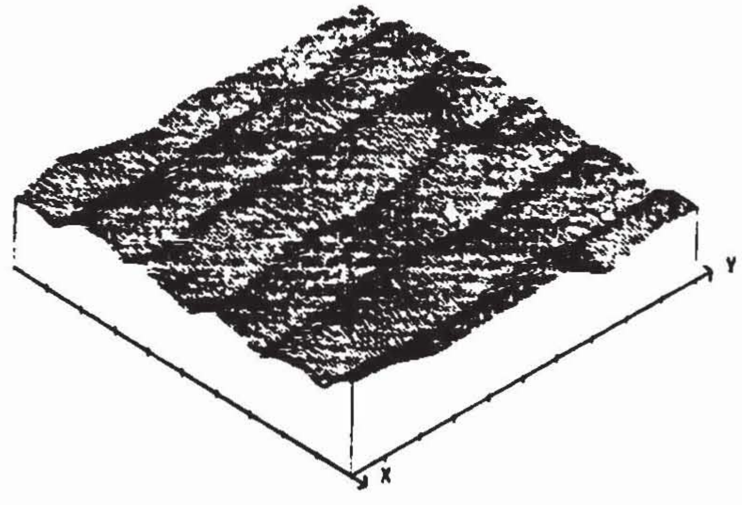

Fig. 8 3-D-profile of ceramic workpiece

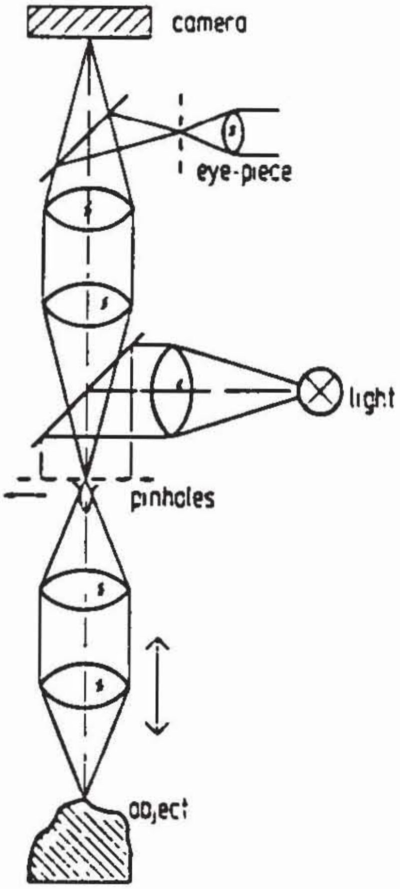

Fig. 9 Arrangement of confocal Microscopy

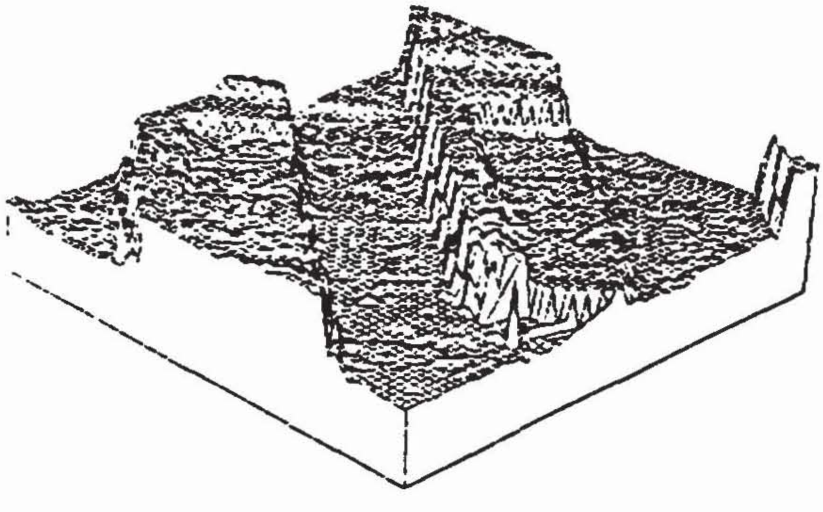

Fig. 10 Result of a 3-D-analysis with image processing of a microchip with the confocal arrangement, resolution 20 nm

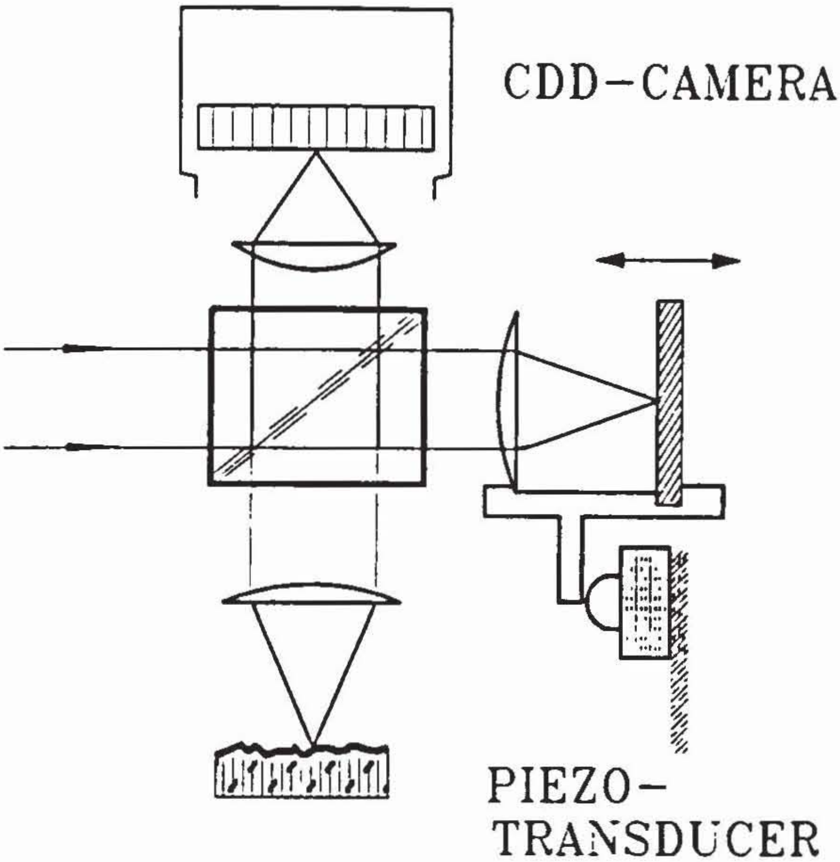

Fig. 11 Modified interference Microscope

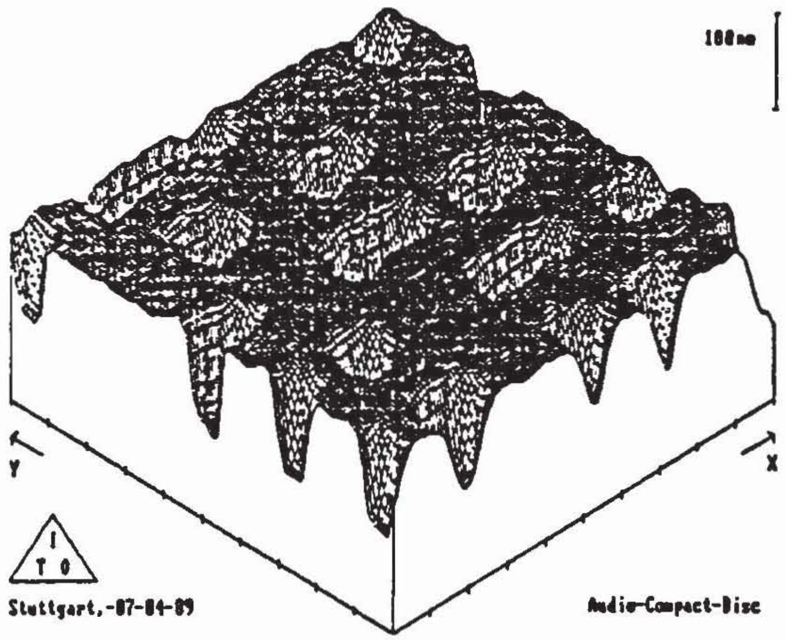

Fig. 12 Microtopography of a CD disk using Fringe analysis

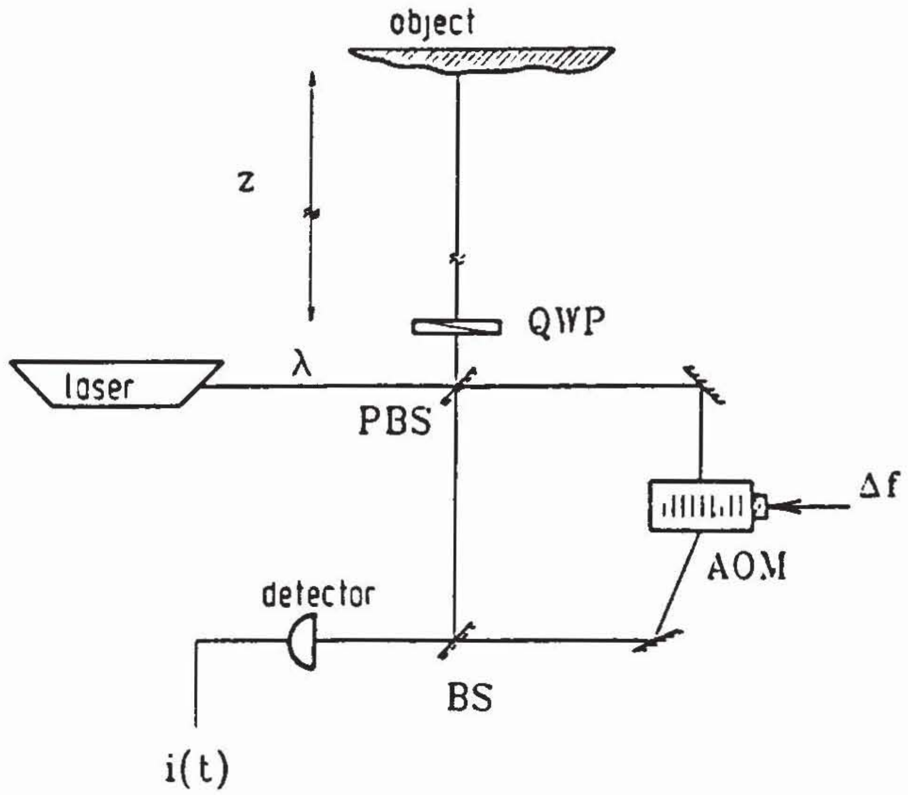

Fig. 13 Heterodyne Interferometer for profile measurements

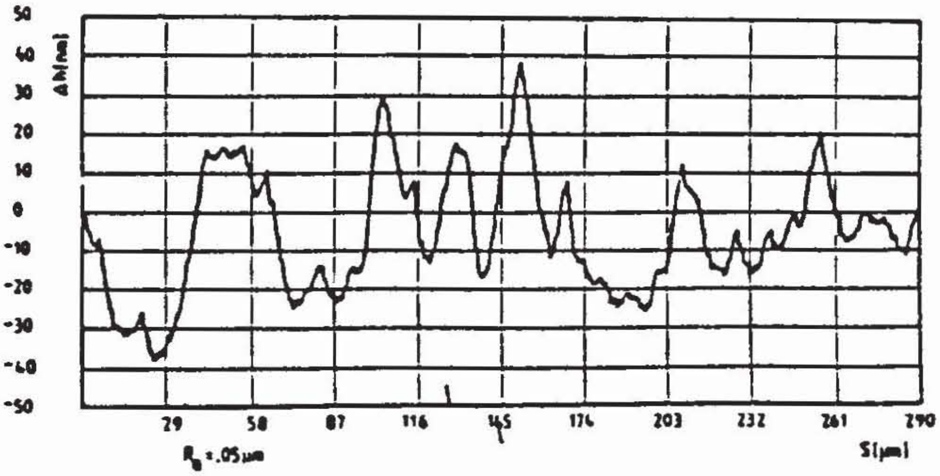

Fig. 14 Profile of a mirror like structure obtained with heterodyne interferometry

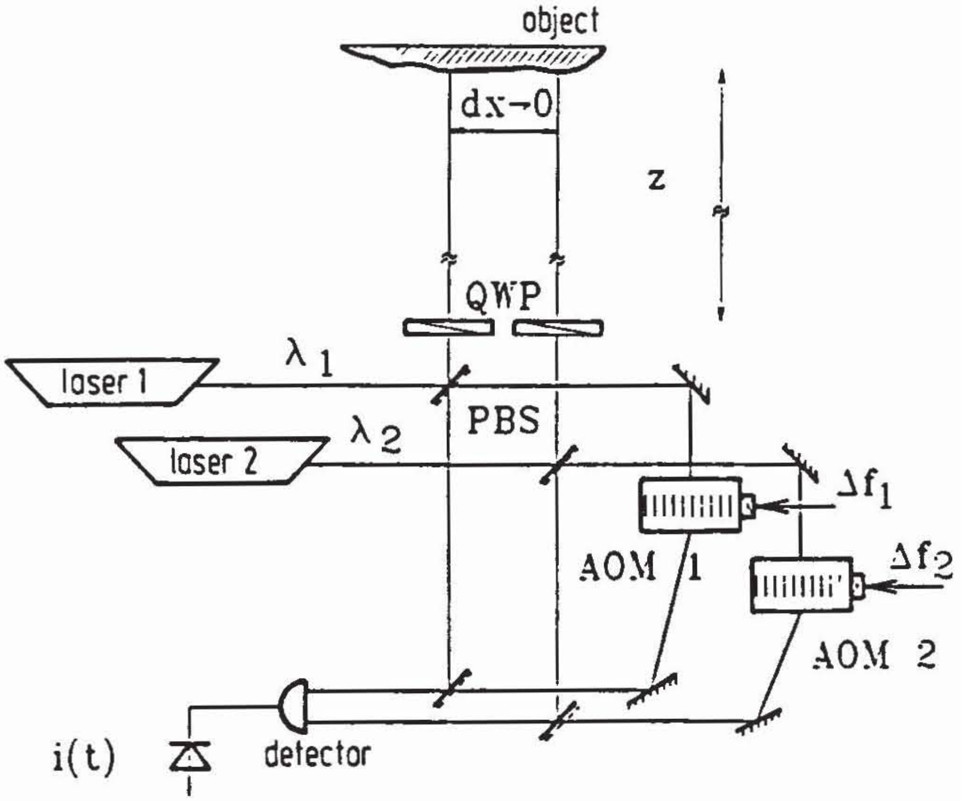

Fig. 15 Doppelheterodyne for Ranging