Optica Applicata, Vol. XXV, No. 2, 1995

Medical applications of photogrammetric methods with structural illumination

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The principles and applications of the projection moire and grid/fringe projection methods for the shape determination in medicine are reviewed. The attractiveness of the methods due to their non-invasive and non-contact character is emphasized. The measurements are whole field and can be readily automated. The application examples are included.

1. Introduction

Optical methods offer several advantages for diagnosis purposes in medicine. They are non-invasive and non-contact, the measurements are whole-field (in contrast to point-by-point methods), data acquisition and processing are relatively fast so that investigations can be done in quasi-real time and the process automated.

Non-contact shape and deformation measurements are of growing importance in medicine. This is because 3-dimensional information is much more complete than 2-dimensional one, leading to better diagnosis and therapy assessment. Several optical methods can be thought to be used for that purpose, *e.g.*, holographic and speckle contouring and photogrammetric techniques using structural illumination. Taking into consideration the experimental set-up and/or apparatus simplicity and the required resolution of the order of tenths of a millimeter, the photogrammetric methods appear as the best choice. The applications include the profilometry of external (*e.g.*, human back examinations for postural deformity studies) and internal (larynx, stomach) human and/or animal organs.

This paper reviews recent medical applications of photogrammetric methods with structural illumination. The emphasis is placed on the projection moire and grid/fringe pattern projection methods, which allowed us to handle the objects within a wide dimension range and are relatively easy to automate.

2. Projection moire

The principle of the projection moire method is well known (see, for example, [1]). The periodic structure is imaged onto the surface under test. As surface profile under study deviates from a plane, the projected lines are no longer straight and equidistant. The observation system images them onto a second periodic structure and moire fringes are formed. Provided certain geometrical conditions are fulfilled in the system [1], the moire fringes follow the contour lines of the object surface.

Several implementations of the above principle have been presented, mostly for the purpose of postural deformity studies (among most recent publications see [2], for example). Figure 1 shows the diagram of the projection moire system built for that purpose at the Institute for Design of Precise and Optical Instruments of the Warsaw University of Technology [3], [4].

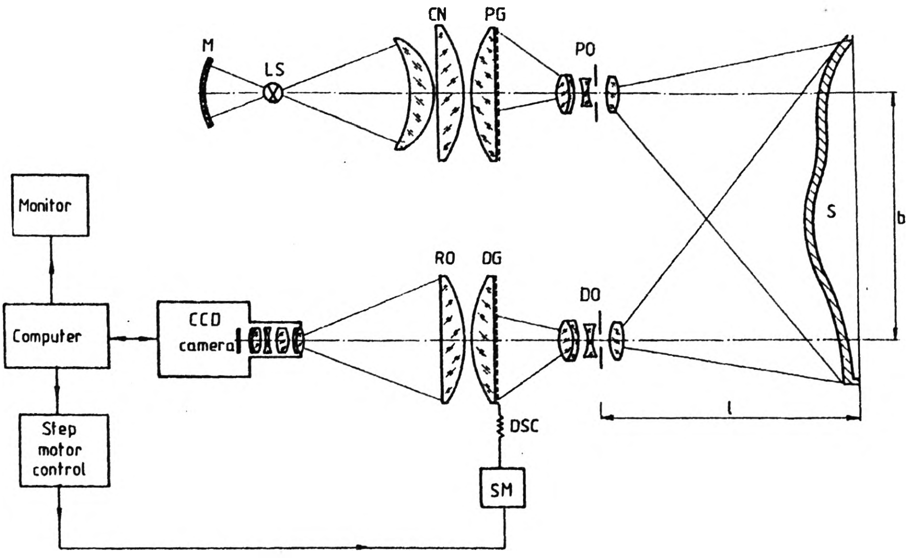

Fig. 1. Schematic representation of the projection moire system. LS — light source, M — mirror, CN — condenser, PG — projection grating, PO — projection objective, OB — object under test, DO — detection objective, DG — detection grating, RO — relay optics, SM — system motor, DSC — driving screw control

The projection distance can be varied from 1.5 m to 4.5 m. The maximum field size is 1200 mm × 800 mm. With gratings of density of 10 lines/mm, the distance between the optical axes of objectives PO and DO equal to 350 mm, and the projection distance of 4.4 mm, the basic fringe contour interval is 25 mm. After applying the automatic fringe pattern analysis algorithm the accuracy of the human back shape determination is ± 1.25 mm or better.

The temporal phase stepping method (see [1], [3], [4], for example) using the four-frame algorithm ($\pi/2$ phase shift between subsequent images is implemented by programmed displacement of the detecting grating) is mainly used for automatic analysis of moire fringes. The algorithm choice is dictated by the compromise between the accuracy and the image acquisition time. Four sequential images are read into the computer memory so that four intensity values are stored at each pixel location. The phase calculated from the arctan function is then unwrapped to obtain a continuous phase function. The latter one is subsequently used to determine the object height.

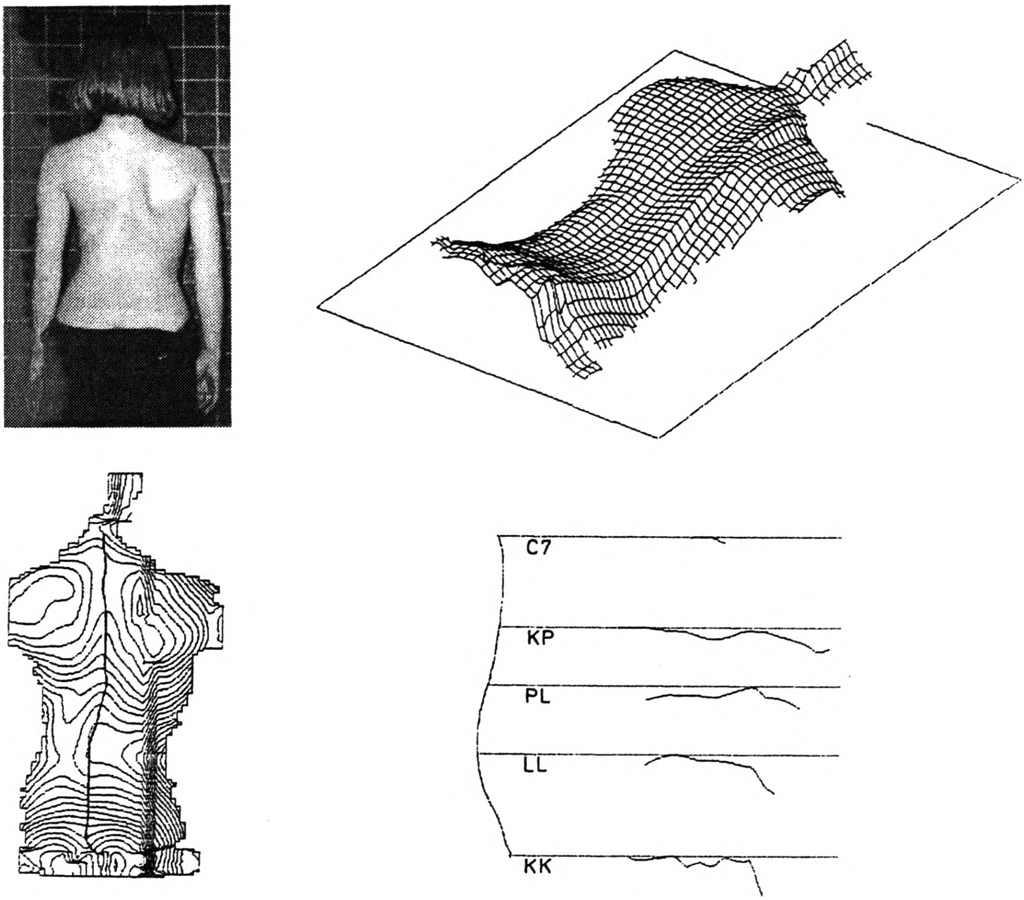

Fig. 2. Postural deformity studies of a person with lateral spine curvature [4]. C7 – vertebra, KP – peak of kyphosis, PL – transition point from kyphosis to lordosis, LL – peak of lordosis, KK – sacral bone

The absolute object shape is calculated by subtracting the shape of the reference surface. For this purpose a plane surface is inserted instead of the object and the reference height, including the system errors, is determined first by the same phase stepping technique. Next, this value is subtracted from the patient data.

The medical software developed [5] enables routine image analysis in three body planes for free standing position: *sagittal*, *frontal* and *transverse planes*. Below, a short software characteristic is given following the description presented in [4].

In the *sagittal plane*, first some general parameters are calculated and analysed such as the vertebral column length, body and trunk inclination angles, global value of curvatures and the angular balance factor in this plane. Next, the system analyses the individual curvatures from the point of view of their length, depth, angular values and mutual relationships.

In the *frontal plane*, the general data are presented first as well. They are related, for example, to body and trunk inclination angles and the localization of shoulders, shoulder blades and waist angles including their directions and possible asymmetry values. Subsequent analysis concerns the vertebral column itself. In this case, the lateral spine curvature is found, its localization and direction(s) of deflection(s) are determined and detailed linear and angular parameters of the spinal curvature are calculated. Possible secondary curvatures are determined as well. The image analysis enables linear and angular spinal curvature compensation.

In the *transverse plane*, the posture analysis can be conducted at predetermined levels (*e.g.*, peaks of particular curvatures in the sagittal plane or the peak of lateral curvature). The cross-sections in this plane are analyzed from the point of view of symmetry. The rotation component of possible postural deformity, the localization and the value of trunk deformation can be determined in this way.

All calculated data are registered on a disc in the form of individual patient sets. As required, the data can be presented or reanalysed, usually as the reference data for subsequent tests of the same person. Some tests can be presented graphically. The results stored in the data base are completed by the results of subsequent tests.

An exemplary result of postural deformity studies obtained using the projection moire system and medical software described above is shown on the next page. Detailed description of the parameters indicated as well as some other ones can be obtained on request.

An interesting application of human back contouring is the assessment of the furniture design ergonomics [6]. It is determined by comparing 6 basic parameters selected from 48 automatically analyzed ones (for the standing and sitting positions): shoulder-pelvis asymmetry factor, pelvic twist angle, pelvic inclination angle, shoulders asymmetry factor with respect to the vertebral column and C7 vertebra, and 3D factor (the ratio of the length of the vertebral column along a straight line to the real length of the vertebral column). If the furniture dimensions are incorrectly selected with respect to user's height and body proportions, the values of selected

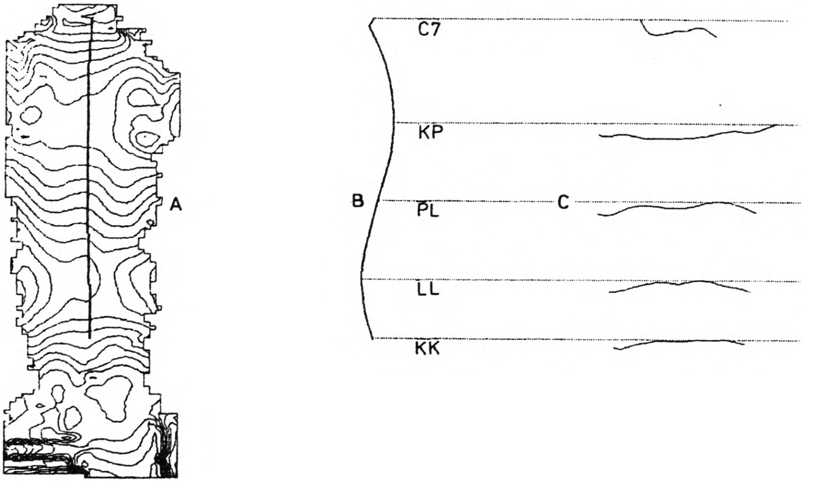

Fig. 3. Graphical presentation of the muscle-osseous system in free standing position: A — frontal plane, B — sagittal plane, C — transverse cross-sections. Symbols mean the same as in Fig. 2 [6]

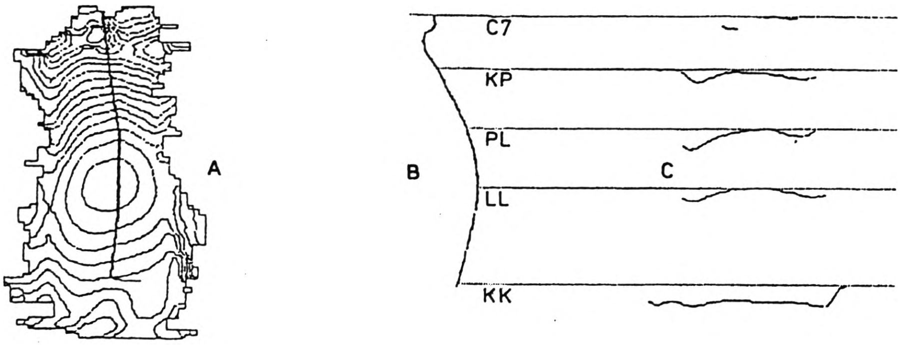

Fig. 4. Graphical presentation of the muscle-osseous system in the sitting position. Symbols mean the same as in Fig. 2 [6]

Postural deformity studies

Patient No. Name
Date of birth Height Weight Right-handed
Date of examination Examin. type 1 (max. exhalation)

Sagittal plane
Global parameters:
Spine length DCK (C7-sacral bone) 527 [mm], *i.e.*, 33.9% of height
Inclination angles [deg]: Alpha 19 Beta 9 Gamma 2 Sigma 0
Trunk inclination angle KPT 177 [deg]
Total value of curvatures 30 [deg] Compensation factor −17 [deg]

Lordosis
Length DLL 375 [mm] (71.2%) Angle KLL 153 [deg]
Length RLL 278 [mm] (52.8%) Depth GLL 56 [mm] (WLL 0.148)

Kyphosis
Length DKP 362 [mm] (68.7%) Angle KKP 169 [deg]
Length RKP 249 [mm] (47.2%) Depth GKP 33 [mm] (WKP 0.090)

Frontal plane
Trunk inclination angle KNT P 1 [deg]
Right shoulder higher by 7 [mm] Shoulder line angle KLB 1 [deg]
Right shoulder blade higher by 5 [mm] Left shoulder blade further by 31 [mm]
Right waist triangle larger than the left one by 25 [mm]
Pelvis: inclination angle KNM L 1 [deg] Twist angle LSM L 3 [deg]
Primary deflection angle approx. 82 [deg]

Lateral spine curvature. At this stage it is possible to determine primary and secondary curvature values and the degree of deformation. Flat back. Distinct asymmetry of shoulder blade location. Visible backward shift of the right shoulder blade. Increased compensation lordosis. Distinct asymmetry of the waist angles.

The results are recorded according to the scoliosis formula for orthopedists.

parameters differ for the two positions. Exemplary graphical representations of the experimental results are shown in Figs. 3 and 4.

The example included shows the possibility of permanently deforming the vertebral bone due to incorrect sitting position. Detailed discussion of the results can be found in [6]. In order to prevent the deformation of the natural posture it is necessary to analyze the muscle tension distribution for particular desk and chair heights, as well as body proportions and the posture type.

3. Grid projection system

The performance of the projection moire system depends on the requirement of object immobility during the time necessary to capture 3 – 5 phase shifted images (for example, in the system shown in Fig. 1 it takes approximately 1.5 s). This requirement is not always easy to meet when, for example, screening school children or diagnosing internal organs.

The solution is to apply automatic image processing using a single frame. Still preferring the phase measuring approach over the intensity tracking one (reduced sensitivity to background and contrast variations in the fringe pattern, automatic sign detection and reduced or eliminated operator interaction), the spatial carrier phase stepping (SCPS) method appears to be an attractive choice [1], [3], [7]. It can be simply implemented by projecting a grid with sinusoidal intensity transmittance or a two-beam interference pattern onto the object under test (see, for example, [8]). The frequency of the image captured by the CCD camera must be properly adjusted – it should be four times lower than the sampling frequency. In this way, the phase in sequential pixel differs by $\pi/2$. The discussion of other basic assumptions to be fulfilled can be found in the references cited. The five-intensity phase stepping algorithm ($\pi/2$ phase shift between sequential pixels) is used due to its self-calibration of linear and quadratic phase shift errors. The phase is calculated from the arctan function (single frame intensity values), unwrapped into continuous phase function and the object height is calculated from the relevant scaling equations [8], [9].

In our laboratory for postural deformity studies we implement the grid projection method by simply modifying the projection moire system shown in Fig. 1. Detection grating (DG) is removed, and as projection grating (PG) the grid with period of 1 mm is used. Due to the use of identical optical systems for projection and detection (PO and DO) the above mentioned relation between spatial periods of the grid image and the CCD matrix period remains constant and independent of projection distance values. It is possible to change the working area and sensitivity by simply changing the projection/observation distance. As in the case of the projection moire method the absolute object shape is calculated by subtracting the shape of the reference surface.

Different design grid/fringe projection systems are used for studies of smaller parts of the human body. Figure 5 shows some exemplary results of morphometric studies of the foot (lateral view).

Till now there is a lack of objective methods for comprehensive assessment of the foot state. In order to get the full information, *e.g.*, to obtain all the required description factors, several methods should be used simultaneously. This makes the diagnosis difficult, and sometimes even impossible. Although some works have already been published [10], [11], the use of photogrammetric methods for foot

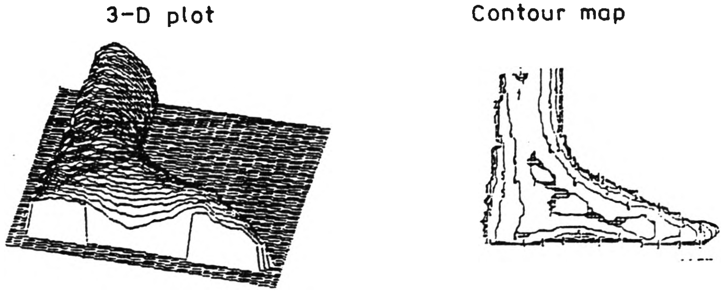

Fig. 5. 3-D plot and a contour map of the foot (lateral view) obtained by the grid projection and SCPS methods (courtesy of M. Kujawińska)

analysis, at rest and under body mass load, still represents a challenge. Under load investigations are especially important in view of applying appropriate therapeutic and rehabilitation procedures.

Structural illumination systems, when miniaturized, can be used to study internal organs. For example, the fibre optic endoscope was constructed with two-fibre bundles: an ordered illumination bundle for object illumination, and a commercially available gastroscope for image transmission [12]. The intensity scanning approach was used to study the shape encoded fringes – the results of preliminary studies of a cat stomach were presented.

Wosiński and Schumann [13] proposed to use interference fringes produced by two beams emerging from two single-mode fibres (the fibre ends of 5 μm core diameter were treated as point sources). A fibre bundle with ordered multimode fibres and wide angle optics were used as the imaging system. The problem with this approach is a restricted resolution as compared to standard camera objective. The application of this fringe projection approach to human tympanic membrane studies is under investigation. Detailed measurements of the shape deformation area changes and volume displacement of the tympanic membrane under static pressure load (freshly dissected human temporal bone) using the shadow moire method were recently reported [14]–[16]. The shape of tympanic membrane is fairly complex and seems to be of significant importance in the coupling of the acoustic sound pressure in the external ear canal to the motion of the middle ear ossicles.

Another use of interference patterns (virtual gratings) for small medical object surface contouring (tooth imprints and wear measurement in dental restorations) was reported by Jongsma *et al.* [17], [18]. A Sagnac interferometer with modifications to generate tunable interference patterns was used to generate additive moire fringes with periods of the order of a few micrometers.

Finally, the recent works of Stultiens and Jongsma [19] and Jongsma *et al.* [20] concerning the measurement of the shape of the cornea should be mentioned. As is well known, the shape of the cornea is an important parameter of the human eye, since the corneal shape determines part of a person visual acuity. Diffusely emitted images obtained from two orthoscopically projected grids on the cornea (modified additive moire projection [21]) were Fourier-analysed. With certain improvements in hardware and extra digital filter techniques in software, the corneal height image was reconstructed with an axial resolution of 3 μm and a lateral resolution of approximately 40 μm × 30 μm in 21.5 × 14.5 mm^2 measurement area. The authors mentioned several clinical advantages of measuring the shape instead of the local slope of the cornea.

Acknowledgements — The author is much indebted to Dr W. Niesłuchowski of Rehabilitation and Spine Disease Clinic VIGOR and Dr D. Zawieska of INFOMED LLC for providing the test results shown in Fig. 2, to Dr I. Nikołowa—Burzyńska of the Institute of Wood Technology for providing the materials on furniture ergonomics studies and to Dr M. Kujawińska and M. Pirga for discussion and help during the experiments.

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Received, May 17, 1995