LEAST SQUARES METHODS FOR SURFACE RECONSTRUCTION FROM IMAGES

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Abstract:

Object surface reconstruction from digital image data is a subproblem of Computer Vision. It has found a widespread interest in many technical and scientific areas in these days, not only in photogrammetry. This paper reviews at first the recent developments of sur- face reconstruction from images in photogrammetry, where the correlation methods have evolved from step-by-step and patch-by-patch procedures to unified least squares surface methods. By this way digital image matching, DTM generation and orthophoto computation have been combined into one approach. On closer inspection the new theory shows up as rather complete, general and flexible, equally well suited for all kinds of multisensory and multispectral imagery. On the other hand, this photogrammetric contribution to Computer Stereo Vision may receive much benefit from the algorithmic research that has been pushed forward on a very high level in Computer Vision. These results still have to be integrated into the basic approach to overcome the considerable computational burden, e.g. very large number of parameters to be estimated, convergence, surface discontinui- ties, occlusions, surface disturbances. Discussions on these topics and a rather long list of references should give an aide for future solutions.

Keywords: Review, digital photogrammetry, image matching, digital terrain model, image processing, geometric processing.

1. Introduction

1.1 Mathematical concepts, computational procedures and data base considerations of image correlation or image matching, of Digital Terrain Models (DTM) and Geographic Information Systems (GIS) or systems for Computer Integrated Manufacturing (CIM) are coming together, sooner or later. Therein, the part of object surface reconstruction is integrated as an information capturing and information processing tool in a GIS or CIM environment. This is one of the general observations of this 1984 - 1988 review of refe- rences, chap. 6. In this paper, however, we are not going to tell the whole story. Instead, we restrict ourselves to the following topics:

- the evolution of image correlation concepts into DTM computation as a new level of computer stereo vision,
- discussion of additional conceptual elements from scientific fields, other than photo- grammetry, to be integrated into an object surface reconstruction method that could be - as a result - highly adaptable and flexible.

Therefore, considerations on mathematical concepts are preferably reported, and the re- sults of experiments on computational speed, accuracy, data structures, data flow and so on, are only mentioned occasionally.

1.2 During the past decade three major categories of image matching algorithms have emerged (GHAFFARY 1985). The procedures discussed here belong to the signal-processing- based, processing directly image intensity data. Among those we only regard the subset that apply least squares parameter estimation.

There have been many investigations on different optimality criterions from statistical estimation theory (in recent time: EHLERS 1985, LIN 1986, STOKES 1986, VOLLMERHAUS 1987). However, it is apparent that there exists no favorite star among them, being clearly superior over least squares. Nevertheless, the use of other optimality principles may be

attractive for special circumstances. The dynamic programming based techniques, for instance, are very promising for use as a starting procedure to get a first coarse match, but not for high precision (BENARD 1984, BENARD et.al. 1986, KÖLBL et.al. 1986, LLOYD et.al. 1987). Or, with another principle one may succeed even in extremely difficult surroundings, see BARNARD's 'simulated annealing' (BAKER 1984,1987), but at the expense of 'excruciatingly slow convergence' (TERZOPOULOS 1988). Besides further procedures we will not look at either belong to the artificial-intelligence-based algorithms, like relational matching (SHAPIRO/HARALICK 1987), relying on scene features: edges, boundaries, zero-crossings of second derivatives of image gray values, ... (GRIMSON 1984, FÖRSTNER 1986a, SCHENK/HOFMANN 1986, SCHENK 1987). As such, we discuss in this paper so-called low-level vision processes.

Signal-processing-based object reconstruction methods determine only the 'sensor-visible surface' of an object. They cannot per se derive semantic information about objects. In photogrammetry, this situation is the state-of-the-art for now. But very soon, when our surface reconstruction resolution improves and the methods can be applied to large scale air imagery we are forced to skip over or filter out a lot of undesired 'disturbances' from the topographic surface, like trees, hedges, crevices, houses, cars,... ('terrain noise', HELAVA 1988). So, when object recognition potentials have to be included the third category of image matching techniques, the so-called hybrid algorithms (GHAFFARY 1985), will become very important. As we will see later in this paper, the new surface reconstruction approaches offer a favorable step towards hybrid techniques.

1.3 This paper is, so to speak, a follow-up of FÖRSTNER's invited ISPRS-paper from 1984, see reference. I assume most of his findings there will continue to be valid, also when future investigations about the new approaches (chap. 4) will be at hand. So, the period 1984 to 1987 may be regarded in part as a phase of continuation and refinement of image correlation and least squares matching methods and in the other part as a transition phase to unified object reconstruction methods for which detailed investigations just have been started.

2. Bibliography of references from 1984 to 1987

Object surface reconstruction from digital image data is a subproblem of computer vision. In these days it has attained a widespread interest, especially in many technical and scientific fields outside photogrammetry! Although extremely useful, it is almost impossible to compile a complete bibliography of activities in this multidisciplinary area. The references in chapter 6, therefore, represent rather a personal choice of my own than an objective collection.

Some sources, mainly those from photogrammetry, have been surveyed systematically for relevant papers. This survey should be complete: see chapter 6 the first ten sources. The other sources mentioned there have been exploited in part, but are highly recommended for further reading, see also SHAPIRO/KAK 1985, FÖRSTNER/WIESEL 1985, FÖRSTNER 1985. Finally I would like to guide your interest to the excellent bibliographies of A. ROSEN-FELD 1985, 1986, 1987, published every year in CVGIP. These surveys on mainly USA-activities cover more than 1200 references arranged by subject matters.

3. Towards unified least squares methods

The methods for object surface reconstruction we are looking at in this chapter may all be categorized under two aspects:

● They have been modeled as image matching approaches in that sense that corresponding gray value patterns of a patch from one image are searched in a second image (eventually also in a 3rd, 4th,... image) after some geometric and radiometric transformation.

● The final results are computed step-by-step thereby reconstructing the object surface point-by-point or patch-by-patch.

In it's simplest form 2D-image matching has been modeled with a 4-parameter-transformation: 2 translational parameters for the geometric part and also 2 parameters for a linear signal transferfunction. As a solution procedure the maximization of the signal correlationfunction (the famous product moment correlation function applied to image gray values) has been widely used. It is well known that correlation maximization and parameter estimation by least squares, thereby minimizing the residuals of the image gray values are equivalent procedures (EHLERS 1985, FÖRSTNER 1984). Even this simple image matching method may successfully be applied for suitable tasks. EHLERS/WELCH 1987 have computed a DTM and contour map from Landsat TM imagery with an accuracy of ± 42 m RMSE for height values resp. ± 0.3 pixels.

BOOCHS 1984, 1987 also has used the standard 2D-correlationfunction even for 1:12000 air imagery. But prior to image correlation a small inclined plane at the object's surface is introduced for a better image rectification (image shaping). The computational steps are controlled from object space presupposing interior and exterior orientation of imagery: Correlation, plane determination and rectification are alternating as long as necessary. After BOOCHS this procedure has shown to be as accurate as an operator; see also BOOCHS/DECKER 1986.

A conceptionally very important improvement had been originated by ACKERMANN and his team (ACKERMANN 1984) in Stuttgart:

● First they expanded the geometric patch mapping from image to image into a complete linear 6-parameter-transformation, corresponding to an inclined plane patch in object space. In all, this matching model comprises 8 parameters. As long as the patch can be kept small enough this is already a good surface approximation for a local area. Later, data of interior and exterior orientation of imagery have been considered in that approach (FÖRSTNER 1986c).

● However, of major impact has to be regarded the conversion of iterative correlation maximization into a conventional nonlinear least squares estimation procedure, thus very much easing all kinds of statistical investigation.

Based on the 8-parameter model intensive investigation and much progress in understanding Computer Stereo Vision have been initiated from Stuttgart (ACKERMANN 1986, ACKERMANN/SCHNEIDER 1986, ACKERMANN et.al. 1986, FÖRSTNER 1984,1986a-d, FÖRSTNER/GÜLCH 1986, PERTL 1985,1986, TORLEGÅRD 1986b,1987, GRÜN 1985). Of the fundamental findings with a strong impact on the reconstruction process of an object surface with that approach we mention the following: Digital image matching can successfully be applied in areas of non-zero gray value gradients. To be more precise, it can attain high accuracy depending on how low signal noise and how low signal gradient noise are, or - equivalently - how large signal correlation and how small signal bandwidth are (FÖRSTNER 1986c).

Air imagery from earth topography very often show considerable gaps of insufficient signal quality to allow for digital image correlation. There are many proposals to solve this problem by by-passing those critical areas with the assistance of so-called interestoperators (FÖRSTNER 1986a,c, FÖRSTNER/GÜLCH 1987, LUHMANN/ALTROGGE 1986, PIECHEL 1986) or salient-point-identification (after Haggag, see DOWMAN 1984). With them, in a preprocessing step of image matching points or patches in image space may be detected with best chances for a successful, accurate and reliable least squares match.

However, computer stereo vision in general belongs to the class of ill-posed inverse problems (TERZOPOULOS 1986,1988). Therefore, every chance to improve the computational stability of image matching is very important. For that GRÜN (1985a,b, GRÜN/BALTSAVIAS 1985) has included all available geometrical constraints. For a stereo pair of images the knowledge of interior and relative orientation have already a strong impact on least squares image matching, thus forcing a 2D-image window to move along the corresponding epipolar line and with a reduced deformation, or - equivalently - the earlier mentioned 8-parameter-transformation may be reduced to only 5 parameters. The effectiveness of geometricly constrained least squares image matching has clearly been demonstrated by GRÜN/BALTSAVIAS 1986. As far as accuracy is concerned no significant difference against

an operator's high performance has been ascertained.

There is another constrained image correlation, called Vertical-Line-Locus method (= VLL), which is the principle of the correlator in the analytical plotter DSR-11 from Kern (ALMROTH/HENDRIKS 1987, BENARD et.al. 1986, KÖLBL et.al.1987, LI 1986). With VLL the 2D-windows of images are allowed for move on nadirlines only. Experiments have demonstrated a high reliability and a rather good accuracy, however, not surpassing an operators performance. Less flexible image shaping (obviously due to the simple correlation function used) may be the reason.

Similar stabilizing effects from constraints are true for 1D-image matching along profiles if organized as epipolar line correlation (HOBROUGH 1978, PAPE 1984, CLAUS 1984, PIECHL 1985). However, experience with FAST Vision (WAMSER 1986) has evidenced that 2D-image matching in general will be superior. Before we further continue the review of image matching concepts and surface reconstruction we mention briefly some applications of least squares image matching. Most of the activities are related to close-range tasks of photogrammetry. Very often these are experimental studies.

In Stuttgart least squares image matching has been tailored for measuring industrial work pieces, especially for motor-car industry (SCHEWE/FÖRSTNER 1986, SCHEWE 1987). Standard close-range photography of workpieces has to be taken. Subsequently the photographs are put into an appropriately equipped analytical plotter from Zeiss (Oberkochen). The photos are automatically digitized, evaluated by least squares image matching and the results are structured for direct use in an industrial CAD-environment (CLAUS 1987). EL-HAKIM 1986 and WONG/HO 1986 each have established an experimental set-up for real-time digital CCD stereo-imagery and it's evaluation. Both apply epipolar line correlation. Very popular and very quick for use in industry are the methods working with structured light (MAGGEE/AGGARWAL 1985, HORN 1987). They are designed under the dictatorship of real-time performance. The correspondence task in stereo image pairs, therefore, has to be eased by dedicated hard- and software. FÖRSTNER 1986b has discussed several coded binary pattern for solving the correspondence problem. Often active illumination with a moving texture is employed synchronized with digital cameras for taking stereo imagery. MURAI et.al. 1986b project line after line of a gridded pulse-pattern on the object where each pulse is of different intensity (out of an 8 bit dynamic range) to be easily detectable. In many other methods one of the stereo cameras conceptionally is replaced by a calibrated texture projector (e.g. FROBIN/HIERHOLZER 1985, TURNER-SMITH/HARRIS 1986, WANG et.al. 1987). So, there is much information about the texture projected on the object's surface that is used to advantage for object surface reconstruction. In the most extreme case the texture may be just one very bright spot per frame (KEEFE/RILEY 1986, HAGGRÉN/LEIKAS 1987). It is obvious that image matching under these circumstances becomes a trivial job: extremely reliable, accurate and very quickly performed.

After all, these sketched methods ob object surface reconstruction in close-range may be regarded as specialized, yet simpler cases of general stereo vision we have discussed earlier. Because, there, almost no information about object surface texture is given in advance that could be introduced into the design of computer stereo vision concepts.

At this point of our considerations we may sum up the following interim statement: Under general conditions least squares matching methods reviewed so far will produce surface data point-by-point (or at best patch-by-patch) in an uneven distribution completely depending on the quality of object surface texture. Also, consecutive computational steps are necessary to reconstruct the surface of an object from scattered data.

The work of GRÜN (1985a,b, GRÜN/BALTSAVIAS 1985, 1986, 1987), ROSENHOLM (1986a,b, 1987a, b) and RAUHALA (1986,1987) has marked important steps toward unified surface methods. GRÜN not only has introduced geometrical constraints into image matching as already mentioned but also integrated the object surface reconstruction into that process. He further showed that more than two images could be processed together. For surface representation a set of connected plane patches has been proposed. ROSENHOLM also starts from least squares image matching, but he proceeds to a better adaptible surface reconstruction. The constant term of the above mentioned constrained 5-parameter window

transformation, representing a constant x-parallax for a total window of a reference image relative to a slave image, is now expanded into a 2D image space function with bilinear finite elements. Surface representations of this type are often applied for DTM generation and other surfaces (e.g. EBNER/REISS 1984, ENCARNAÇÃO/STRASSER 1986, REISS 1985, TERZOPOULOS 1988, TORLEGÅRD 1987). Investigations with air imagery 1:50000 and close-range photography of rock texture have shown primarily an increase of reliability as compared to single patch image matching. ROSENHOLM's approach has similarities to an array algebra matching method proposed by RAUHALA 1986,1987. He also correlates reference with slave images. In their generality RAUHALA's ideas are very interesting. I think, his array algebra and related algorithms may be very useful for the computation of the object surface reconstruction approaches we consider in chapter 4.

Before we close this chapter I would like to remind of some work of HOBROUGH from 1978 (see also PAPE 1984) and from earlier, when it had led to the Gestalt Photomapper (see KOK et.al. 1987 for latest information). At that time HOBROUGH (being the pioneer for many ideas in image correlation) had designed image matching of stereo imagery to take place in object space, after rectification of image windows into orthophoto windows by a DTM that emerges simultaneously in object space. Object space models are also the fundamentals of the new general models for object surface reconstruction.

4. Unified least squares surface reconstruction from image data

4.1 A general and highly adaptable approach: The principle of back mapping image data into object space models

Progress in object surface reconstruction with similar approaches has been attained in the past decade independently at three different places for aught I know. The author of this paper has finished the first two papers about his concept FAST Vision (= Facets Stereo Vision) in 1985. But they were published later in 1987 (see WROBEL 1987a,b), also additional papers with generalizations and some numerical results (WROBEL 1987c,d, WROBEL/WEISENSEE 1987, not published ; WAMSER 1986, WEINGÄRTNER 1987). HELAVA reports (HELAVA 1987,1988) that he has been working with his new approach LSGC (= Least Squares Groundel Correlation) long before publication in 1987 and 1988. The paper of EBNER et.al. has been published only shortly after, also in 1987.

In this paper only a short insight into the main principle is presented. For details and numerical investigations see the references mentioned, also the papers from this congress: KORTEN et.al. 1988, WEISENSEE 1988 and WROBEL 1988.

The inferences from the review in chapter 3 have led to the basic ideas of the new approach for object surface reconstruction:

- Admission of highly adaptable mathematical models with many parameters (without immediately thinking on how to compute them on a PC!).

- Admission of more than the two traditional stereo images for simultaneous evaluation without favoring one of these as reference image. Therefore, no 'slave' images anymore!

- The matching procedure from image to image is regarded as an obstacle and a roundabout way to object surface reconstruction. Therefore, image matching should be done directly from image space into object surface models. So, the term 'image matching' should be given that new meaning!

- Combination of processes separated so far into one unified approach of object surface reconstruction: image matching, DTM generation (surface reconstruction), orthophoto generation (object optical density computation).

- The integration of object optical density (or equivalent object surface reflectance parameters) into image evaluation should throw a bridge between geometric and semantic image evaluation processes (3D image analysis and pattern recognition). Also, multisensory imagery may then be more easily integrated.

- Finally, the conversion of correlation maximization to least squares parameter esti-
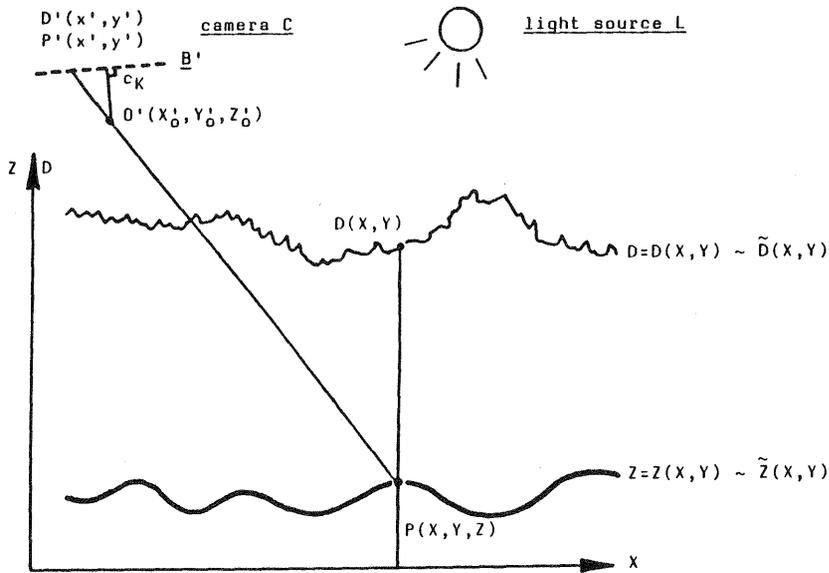
Figure 1:
Two different functions in object space are to be determined: $Z(X,Y)$ and $D(X,Y)$

$\underline{B}'$	digital perspective image of object space X,Y,Z	$P(X,Y,Z)$	corresponding point on the object, centre point of surfel
x',y'	image coordinates in $\underline{B}'$	$D'(x',y')$	digital optical density in P' of $\underline{B}'$
c_K	principal distance of $\underline{B}'$	$D(X,Y)$	optical density on object surface
$O'(X'_0,Y'_0,Z'_0)$	point of projection of $\underline{B}'$	$Z(X,Y)$	object surface
$P'(x',y')$	centre point of one pixel in $\underline{B}'$		
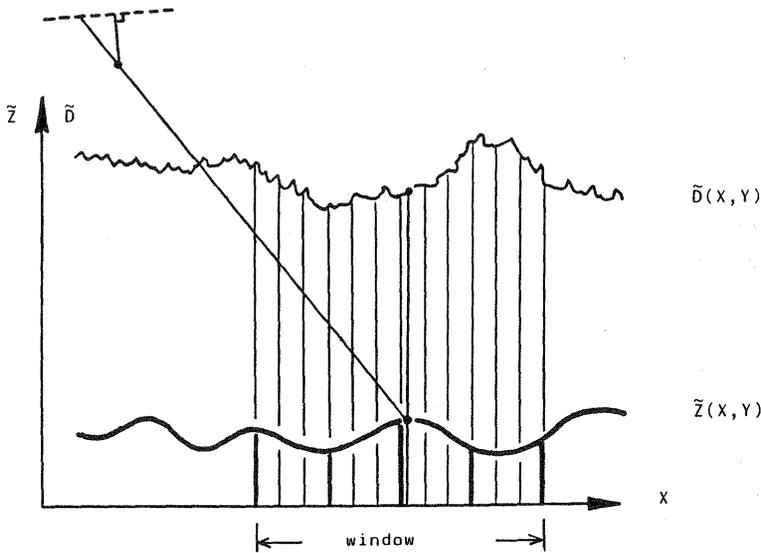
Figure 2:
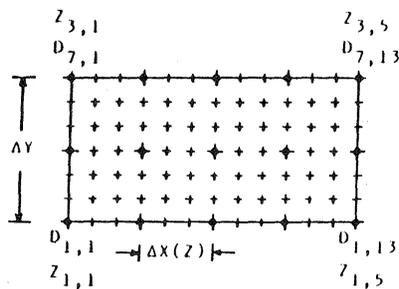
Figure 3:

- Z_{rs} gridvalues of Z- and D-facets, respectively
- + D_{kl}

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mation has proven, see chapter 3, to be a very suitable image data processing tool. It should be retained at any rate, thus allowing e.g. a strict control and error propagation for DTM data.

The basis of the new developments in photogrammetry is - as I call it - the back mapping principle of image data into object space models. We may denote it also as an image inversion approach. In essence it is a mathematical model of what has happened physically between a surface element at the object's surface (= surfel for short), illuminated by a light source, and the gray value G' (resp. optical density D') of the corresponding pixel in image $\underline{B}$', see figure 1. This relationship should be modeled as complete as possible for scientific research, but for actual photogrammetric application we have to be satisfied with a reasonably feasible model. It is composed of several distinct models. They are by no means new. Most of them are object space models. In image space only a sensor model (camera model in figure 1) has to be regarded. More detailed discussions on image formation and reflectance functions of object surface are given by WEISENSEE 1988. In this paper we assume for the object the simple Lambert-reflectance property. Then, in a general formulation the back mapping relationship reads as follows:

$$D'(x',y') + v_{D'}(x',y') = D' \{C(x',y';p_{C,j}), \tilde{D}(X,Y;D_{kl}), \tilde{Z}(X,Y; Z_{rs}), L(X,Y; p_{L,t})\}, (1)$$

wherein on the left hand side we have the observed, measurement quantity $D'(x',y')$ from image space, the right hand side implies altogether a synthetic photorealistic image model $D' \{...\}$. $v_{D'}(x',y')$, the difference between both, should be a random residual. Explanations (see also figure 1):

(2) $D'(x',y')$ optical density of pixel x',y' in image $\underline{B}$'; they are the 'observations' for surface reconstruction

(3) $v_{D'}(x',y')$ the stochastic component of image signals $D'(x',y')$

(4) $Cov(D')$ variance-covariance matrix a priori of D'

(5) $C(x',y';p_{C,j})$ camera model with geometric (interior and exterior orientation) and radiometric parameters $p_{C,j}$, $j = 1,2,...$ If the camera is calibrated and oriented all parameters should be known.

(6) $\begin{vmatrix} x' \\ y' \end{vmatrix} = \underline{x}' =$

     $= \underline{x}'(X,Y,Z; p_{PT,i})$ perspective transformation between image space x',y' and object space X,Y,Z with $p_{PT,i}$, $i = 1,2,...$ as parameters

(7) $\tilde{D}(X,Y;D_{kl})$ representation of object optical density function with parameters D_{kl}, $k,l = 1,2,...$

(8) $\tilde{Z}(X,Y;Z_{rs})$ representation of object surface function with parameters Z_{rs}, $r,s = 1,2,...$

(9) $L(X,Y; p_{L,t})$ illumination model with light source L and parameters $p_{L,t}$, $t = 1,2,...$

For normal air photography the illumination model is constant for all images $\underline{B}$', $\underline{B}$", ... and may be skipped from (1). Also, to keep things simple we did not consider transfer problems of light through the atmosphere. Further, for many applications all camera parameters are available, perhaps without the radiometric parameters. Since the sensed signals $D'(x',y')$ in image space per se are bandlimited observables, overlaid with random noise, the computed functions $\tilde{D}(X,Y)$ and $\tilde{Z}(X,Y)$ as approximations for the real functions $D(X,Y)$, $Z(X,Y)$, will be bandlimited as well. Therefore, corresponding representations may be chosen with D_{kl} and Z_{rs} as sample values, forming altogether connected facets surfaces for both functions (see FAST Vision, WROBEL 1987). But other functions may be suitable as well: the functions used for DTM generation (DÜSEDAU et.al. 1987, EBNER/ REISS 1984, FREDERIKSON et.al. 1985, REISS 1985, SEGU 1985, STEIDLER 1986) or others from Computer Graphics (ENCARNAÇÃO/STRASSER 1986).

For computational evaluation the nonlinear back mapping relationship (1) has to be linearized. We then arrive at an iterative least squares problem: given the pixels from

several images $\underline{B}'$, $\underline{B}''$, ... and their variance-covariance matrices Cov(D'), Cov(D''), ... we may collect all those pixels belonging to the same object window (figure 1-3) and solve the pertaining equations for the parameters of the object space functions $\tilde{D}(X,Y)$ and $\tilde{Z}(X,Y)$, eventually for some camera parameters as well. As such data processing for this new approach also may follow traditional rules of nonlinear least squares estimation, compare e.g. ORTEGA/RHEINBOLDT 1970 for a variety of suitable procedures, Gauss-Newton and so on.

To work with the image back mapping principle for photogrammetric applications, like DTM, there now are some design problems to solve. We mention just this one: Given some digital images $\underline{B}'$, $\underline{B}''$, ... taken according well-established photogrammetric rules, also the pixel size and the matrices Cov(D'), ... of the optical density values are known. Which window size should be chosen? How many images? How many surfels (resp. pixels) per D-facet? And how many D-facets per Z-facet, so that finally a certain accuracy and reliability for $\tilde{Z}(X,Y)$ could be attained? Some of these early questions about this new approach have been demonstrated by KORTEN et.al. 1988. It shows up very soon that a before-hand design of the diverse facets in many applications is not advisable (see chapter 4.2). The design has to be made scene-dependent. For that the data processing has to be supplied with a high potential of adaptability. However, this demand can be met since we apply least squares parameter estimation. All kinds of regression diagnostics may be considered (compare GRÜN/BALTSAVIAS 1985, ROSENHOLM 1986a, BELSEY et.al. 1980).

Let us stop for a moment and let us ascertain whether we have given the proper term to the new object surface reconstruction method. The method obviously is really new because looking back at the main relationship (the image inversion approach (1)) and at the least squares principle for data processing we have to recognize that the traditional photogrammetric term 'parallax' and in particular the famous, for a very long time indispensable term 'correlation' do not appear any more! Therefore, to use them further in this context would be completely misleading! In my opinion the correct term for the new approaches is surface reconstruction by adaptive least squares image matching ('matching' interpreted in that sense that images are mapped back into object surface models) or simply adaptive least squares surface reconstruction from image data.

Generalizations

The basic approach (1) allows many generalizations. They may be achieved by equivalent exchanges of models or quantities in the positions from (1) to (9). In this paper only some indications are given.

Multispectral images

The measurement quantities $D'(x',y')$ and $v_{D'}(x',y')$ in image space and the optical density function $\tilde{D}(X,Y)$ in object space have to be treated as vectors.

Multisensory images

Intensity-type images (like those from optic and photographic sensors) from active or passive scanners, from imaging radar or sonar may also be processed with relationship (1). In the last decade there have been some investigations about the interrelations of DTM and object reflectance (SMITH et.al. 1980, DOMIGK et.al. 1984, WANG et.al. 1984, ROYER et.al. 1985, WILDEY 1986, KWOK et.al. 1987). For robot vision the typical disadvantages of video images can be complemented by range images, if the sensor data are simultaneously evaluated (MAGGEE et.al. 1985, LEVI/VAJTA 1987, RACZKOWSKY 1988). This again is feasible with the back mapping principle (1). For range image data this relationship is simplified by omitting $\tilde{D}(X,Y; D_{kl})$.

Photometric Stereo Vision

For photometric stereo vision images with different illumination models $L(X,Y;p_{L,t})$, see (9), have to be taken (HORN 1987). Also, the object optical density function (7) has to be replaced by an appropriate reflectance function, in the simplest case by the scalar valued Lambert reflectance function $\tilde{R}(X,Y)$.

4.2 Further computational elements for integration into the surface reconstruction procedure

Numerical experiments with the least squares surface reconstruction method FAST Vision (WAMSER 1986, WROBEL/WEISENSEE 1987) have clearly proven that this approach can be applied for both C^o-smooth optical density function $D(X,Y)$ and object surface $Z(X,Y)$ without difficulties. However, these favorable object properties exist very rarely. Therefore, operational computer stereo vision software has to be supplied with additional features. For the remainder of that chapter I just would like to guide the reader's interest to the main problems and give some hints for references. A large amount of scientific research work has already been published in the computer vision world. These results could be transfered and adapted to the specific demands of photogrammetry. Many important contributions in recent time have been presented in particular by WITKIN et.al. 1987 and TERZOPOULOS 1986, 1988 (see also OLSEN 1986). Both have consequently applied techniques from general iterative methods (ORTEGA/RHEINBOLDT 1970) and from finite-element algorithms.

● Regularization

Object surface reconstruction from images belongs to so-called nontrivial inverse problems and is regarded as ill-posed. Small radius of convergence, slow convergence and difficulties to guarantee a unique and stable solution are the main consequences. To overcome the problem interpolation with continuity control functions ("thin plate surface under tension") is applied, with several parameters for local tension control, etc. A similar approach has been used for DTM generation in photogrammetry (e.g. REISS 1985, DÜSEDAU et.al. 1987).

● Multi-resolution image processing and object surface reconstruction

To overcome the general problems of image inversion very often multi-resolution procedures have been proposed and successfully applied. Typically, at first the problem is transformed to a very coarse scale (mostly by appropriate low- and band-passfilters) and may thus easily be solved. The final solution is found working from coarse-to-fine in a pyramid of discrete steps. Thus in particular a by-passing of local minima of least squares can be managed. Multi-resolution procedures habe already been used for long: see HOBROUGH 1978, HATTORI et.al. 1986, O'GORMAN/ANDERSON 1987, ROSENFELD 1984. Recently, WITKIN et.al. 1987, TERZOPOULOS 1988 have applied the well-known continuation method from the theory of nonlinear equations (ORTEGA/RHEINBOLDT 1970, p.230). Now, very conveniently the optimal solution can be controlled and tracked from coarse-to-fine in a continuous mode.

● Solution of large systems of nonlinear equations

Besides the many traditional Newton-Gauß solution procedures in these days multi-grid relaxation has been very much favored. TERZOPOULOS 1983 (see also EBNER/FRITSCH 1986b) has demonstrated that multi-resolution surface reconstruction based on multi-grid relaxation methods accelerates convergence dramatically.

I think, for these tasks we discuss here also array algebra algorithms (RAUHALA 1986) could be applied to advantage.

● Discontinuities, occlusions, shadows, creases, cusps, ...

If for surface reconstruction of a real object (e.g. earth topography) patchwise continuous functions are applied the above enumerated phenomenae will cause distorsions in the gray value residuals of least squares estimation, because the deterministic model in relationship (1) will not be correct in that case. To detect and model C^0- and C^1- discontinuities (steps and creases) of object surface some promising methods have been proposed. GRIMSON/PAVLIDIS 1985 have used a statistical hypothesis testing technique thereby exploiting the local distribution of residuals emerging from a preceding smooth surface fit. TERZOPOULOS 1988 also has worked out discontinuity detection and modelling, but he applies deterministic tests from mainly geometric constraints (see also LECLERC/ZUCKER 1987). For general surfaces there still exists the problem of dealing with disturbances, especially occlusions, ...

● Data compression, post processing

After successfully applying least squares surface reconstruction from image data as a
rule additional data processing will be necessary. Presumably for many applications the
very high density of height data emerging from image processing has to be compressed to
a predefined structure.

Comparisons of DTMs photogrammetrically measured by an operator and computed with diffe-
rent interpolation functions have shown that the type of these functions is not very
important. The major keystones are accuracy of the height measurements and their morpho-
logically significant distribution. This distribution then even may be very irregular
and not very dense. In view of these experiences we now have to focus our interest on
data compression procedures that might replace the operator's ability while viewing
a stereo model to recognize the significant features of topography in the presence of
measurement noise and terrain noise. These cleaned data may then be stored in a Geo-
graphic Information System as DTM. So, we actually need new feature-based data com-
pression techniques.

Reading the papers from the past decade there are already many contributions to deal
with these problems: MAKAROVIĆ 1983, 1984a-c, ÖSTMAN 1986, FÜRSTNER 1983, FREDERIKSON
et.al. 1985, 1986. See also the reference lists of ROSENFELD 1985-1987.

5. Conclusion

In the period from 1984 to 1987 digital image matching evolved from simple correlation
approach with few degrees of freedom, therefore with low adaptability and only local
object surface approximation to a general, yet simple least squares surface reconstruc-
tion procedure. The underlying basic principle of image inversion (or image back mapping
into object space) may be regarded as the 'missing link' in the evolution of Computer
Stereo Vision for various reasons:
● It links image matching, DTM generation and orthophoto computation into one, con-
  trollable process.
● It may serve as a general evaluation model for practically every sensor imagery.
● The integration of object optical density (or object reflectance parameters) into
  the surface reconstruction approach may link and ease geometric and semantic infor-
  mation evaluation from images.
Thus, the new approach may bring together digital photogrammetry and the large potential
of Computer Vision, a potential that we need to prepare photogrammetry for the future.

6. REFERENCES
Surveyed Sources 1984 to 1987
BuL   Bildmessung und Luftbildwesen: Zeitschrift für Photogrammetrie und Ferner-
          kundung
CVGIP   Computer Vision, Graphics and Image Processing
IAPRS   Intern. Archives of Photogrammetry and Remote Sensing, Vol. 26, Part 3 and 5
ITC-J   Journal of the Intern. Institute for Aero Space Survey and Earth Sciences
PERS   Photogrammetric Engineering and Remote Sensing
Phia   Photogrammetria: Official Journal of the Intern. Society for Photogrammetry
          and Remote Sensing
PhRec   Photogrammetric Record
T-PAMI   IEEE Transactions on Pattern Analysis and Machine Intelligence
ZfV   Zeitschrift für Vermessungswesen
IPS   Schriftenreihe des Instituts für Photogrammetrie, Universität Stuttgart

Other Sources

FM   Fotogrammetriska meddelanden: Transactions of the Royal Institute of Tech-
         nology, Department of Photogrammetry, Stockholm
FPPD   Proceedings of the Intercommission Conference on Fast-Processing of Photo-
         grammetric Data. Interlaken, June 2-4,1987
ICCV   Proceedings of the First International Conference on Computer Vision.
         London, June 8-11,1987
SPIE   Proceedings of the International Society for Optical Engineering
WIM   Minutes of the Workshop on Image Matching. Stuttgart University, September
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