SOLVING THE DISPARITY ANALYSIS PROBLEM IN SURFACE RECONSTRUCTION OF MICROSCOPIC SAMPLES FROM BIMODAL IMAGE STEREO DATA

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Summary: The contribution describes a set of programs in MATLAB environment providing for stereo-analysis based surface reconstruction in scanning electron microscopy. It primarily deals with a search-and-match method of disparity analysis as the only so far practical in the given environment of SEM. The search criterion - cosine of angle between vectors representing the compared image areas – has been shown to be equivalent to applying a non-linear matched filter. The method is implemented efficiently as a modification of linear matched filter. Further improvement is achieved by using both available imaging modalities thus providing vector image data that can substantially increase the reliability of finding correspondences. Expressing the result of the vector case in terms of two individual scalar cases cuts the computational requirements to a half besides allowing for an additional reliability criterion - comparison of three different though partly dependent criteria. Marginal but for practical success of the analysis important recent improvements, solving some specific problems of SEM stereo analysis, are discussed as well. The contribution briefly summarises the several-years development of the method and its implementation. Details can be found in the previous publications devoted to specific individual problems [1-5].

Introduction

When determining the surface description (vertical co-ordinates of pixels) of a sample in a scanning electron microscope (SEM), two images of the same area differing slightly by the angle of view must be provided, the first one in normal position (perpendicular to the microscope axis) while the other one in slightly inclined position. Quantitative data on the surface description can be obtained algorithmically on the basis of a geometrical model (fig.1), utilising the information contained in the disparity map derived from the stereo couple of images. Providing the reliable disparity map, based on densely looked-for correspondences between both images of a stereo couple, thus forms the key step in the whole procedure. The reliability has been substantially improved recently by implementing possibility of using bimodal images (in back-scattered electron mode and secondary electron imaging modes) of the same area. The theory behind this step explained in terms of 2D matched filters has been reported on in [3-4]; also the used "layered" search-and-match algorithm that achieves reasonable computational complexity while preserving the necessary high density of the found disparities has already been described in detail in [2]. It should be emphasised that the used approach differs from most of current stereo work by not imposing any a-priori constrains to the computed surface and by the correspondences not being limited to only some detected particular points (corners, crossings etc.) but being reliably found also in seemingly contrast-less areas. On the other hand some additional steps had to be implemented in order that the requirements of users would be fulfilled in the extent needed for routine use in practical applications.

Steps of stereo-analysis of SEM sample surfaces:

1. **Providing a couple of stereo-images** in perpendicular position to the microscope axis and in inclined position.

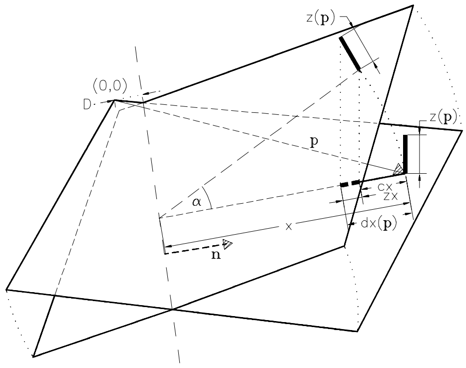

Fig. 1 Geometry of scanning

There are some specific problems during this step:

- tilt-axis position and direction not precisely known (due to imprecision of the sample support working in μm domain),
- possible shift and rotation of the sample between normal and inclined position,
- different contrast in the members of a pair (non-linear brightness transforms).

Bimodal imaging is possible in SEM (two image pairs of the same area, in BEI and SEI modes – fig. 2). This new additional possibility has recently been included in the program.

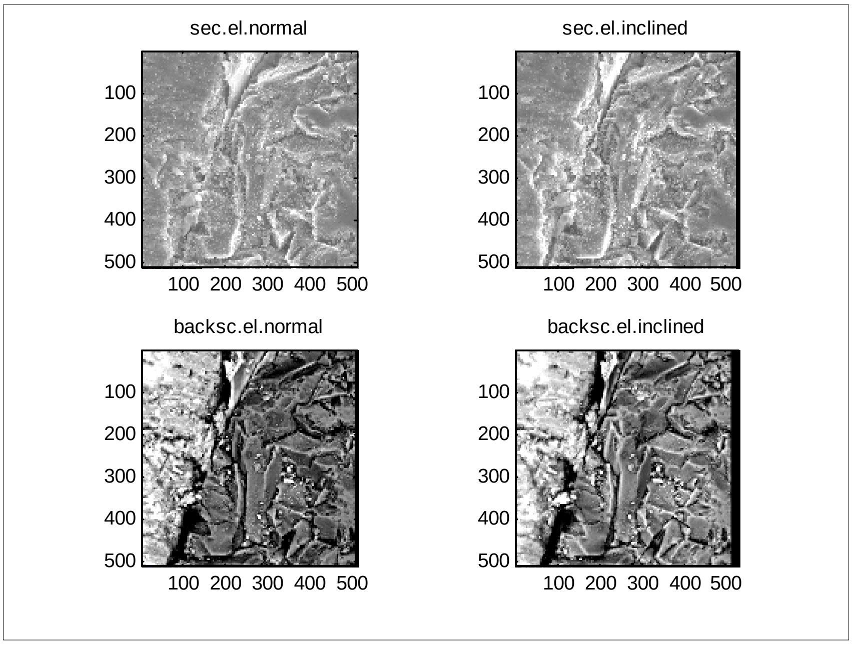

Fig. 2 Example of a quadruple of stereo bimodal images

A new unexpected problem appeared as a consequence*: intermodal mismatch* meaning that the corresponding images of different modalities did not match exactly.

2. **Disparity analysis** leading to a disparity map **d**(**p**) describing the vector shift **d** of individual points **p**=*(x,y)* (in a dense grid, e.g. 256x256 points). Due to diverse surface types, no a-priori constrains to the surface are possible and only detailed search-and-match methods proved acceptable (no few - parameter optimisation turned out applicable).

The typical problems during disparity analysis step are as follows:

- High reliability is requested and consequently the choice of suitable *similarity criterion* is crucial. After extensive comparison of different published criteria, the newly formulated cosine criterion $(\mathbf{a}.\mathbf{b})/(\|\mathbf{a}\|.\|\mathbf{b}\|)$ or even $(\mathbf{a}.\mathbf{b})/\|\mathbf{a}\|$ that is related but importantly different from commonly used normalised correlation coefficient proved best and able to cope well with bimodal analysis:

$$\frac{\mathbf{a}\ .\ \mathbf{b}}{\|\mathbf{a}\|} = \frac{\mathbf{a}_s\ .\ \mathbf{b}_s + \mathbf{a}_b\ .\ \mathbf{b}_b}{\sqrt{\|\mathbf{a}_s\|^2 + \|\mathbf{a}_b\|^2}}$$

- High computational demands for a reliable and dense grid of disparities led to designing s.c. *layered approach* – different from the usual pyramidal concept that would not work satisfactorily. This approach to disparity analysis consists basically in gradually decreasing the size of compared areas while increasing the density of the grid – see [2]. Important speed-up of the computations has been achieved when the non-linear matched filtering was implemented via frequency domain.
- Danger of finding false correspondences in a layer and consequently wrong initial guesses at following layers is rather high during the disparity analysis. Besides other, the main causes of the problem are due to occlusion in one of the images, or due to indifferent (shiny, dark, texture-less) areas or also due to apparent correspondences.

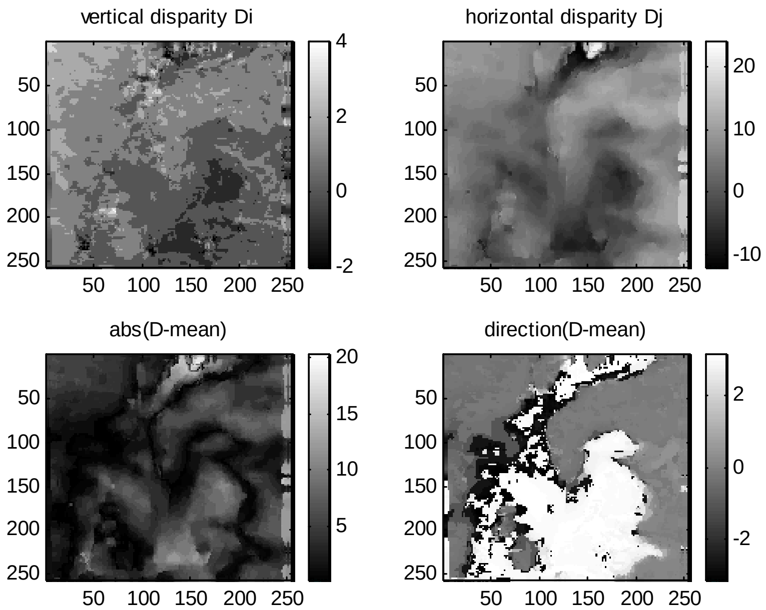

Fig. 3 Example of resulting vector disparity matrix

3. Calculation of the surface based on the disparity matrix and geometry of measurement is described by the following formulae, where z-component (height) at the point **p** is

$$z(\mathbf{p}) = \frac{-dx(\mathbf{p}) - cx(\mathbf{p})}{\sin\alpha}\ ,$$

where

$$cx(\mathbf{p}) = x(\mathbf{p})(1-\cos\alpha) = (\mathbf{n}.\mathbf{p} - D)(1-\cos\alpha)\,,$$

$$dx(\mathbf{p}) = \mathbf{n}\ .\ \mathbf{d}(\mathbf{p})\,,$$

(**a** is the normal to the tilt axis, and α is the tilt angle). Though rather complex, the computation itself is straightforward thus the only, but rather difficult, problem consists in *determining* **n** *from disparity matrix*, as no information on it can be obtained otherwise. An example of the calculated surface as viewed from different directions can be seen on Fig. 4.

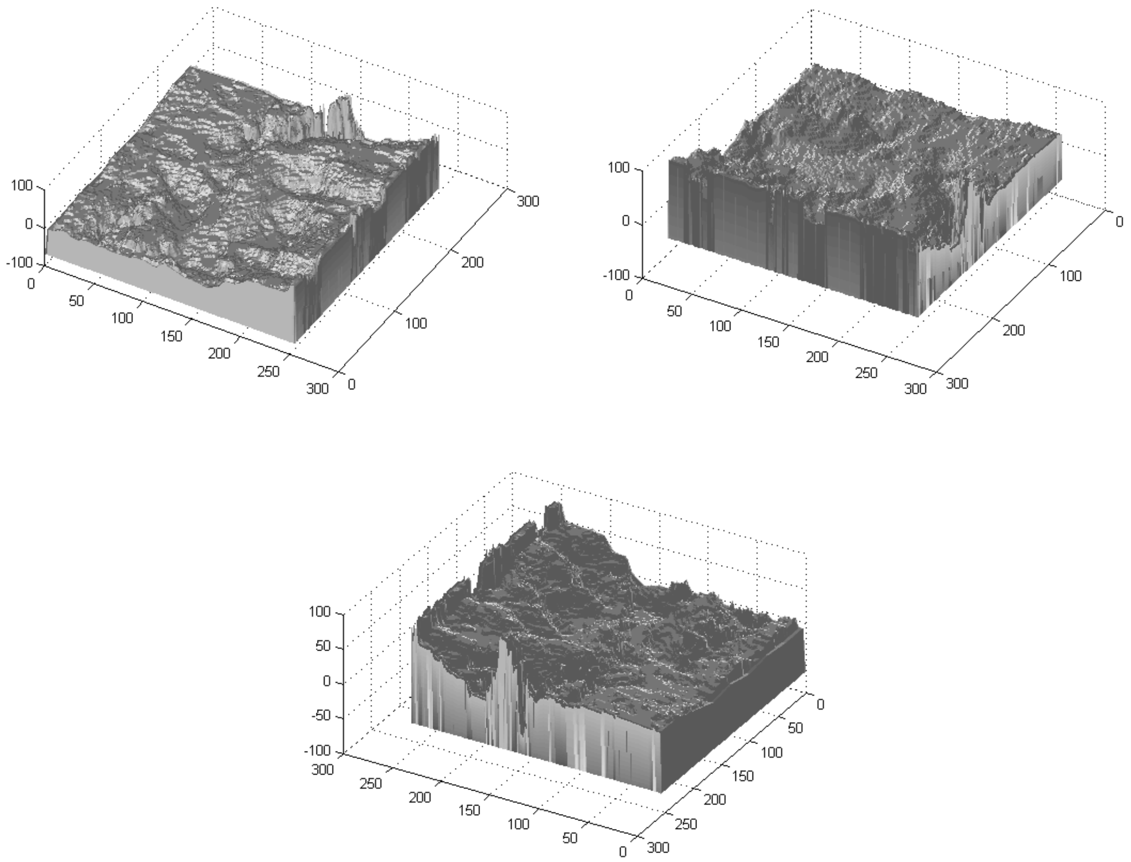

Fig. 4 Example of a calculated surface

Solving the marginal problems

As solutions of the basic problems have already been described previously as indicated, we shall now concentrate to some seemingly marginal, perhaps theoretically not that interesting, but still important problems that had to be solved in order to enable routine use of the method. They are as follows:

- Inter-modal mismatch, probably due to time-instability of sweeping currents, has been found (after some false explanations) to be the cause of not that good results of the bimodal analysis as expected. Presently, it is compensated for by interactive matching, based on averaged two-dimensional translation estimated from nine pairs of corresponding points. It is envisaged that this step be automated by matching based on mutual information criterion, possibly compensating both translation and rotation error.

- Occlusion, indifferent areas, apparent correspondences are dangerous for the proper surface determination as mentioned above. The influence of them has been limited by several measures as follows:

- introducing the *heuristic reliability factor* of correspondences based on approximate agreement of three similarity criteria: from bimodal (vector) images, from BEI mode and from SEI mode,
- verifying correspondences and in case of partial agreement correcting the result automatically,
- marking the questionable points for *interactive check*, and
- enabling interactive corrections when at all needed (only on 1st and 2nd layers).

Several intermediate images from disparity analysis (Fig. 5 - 9) should illustrate the improvements.

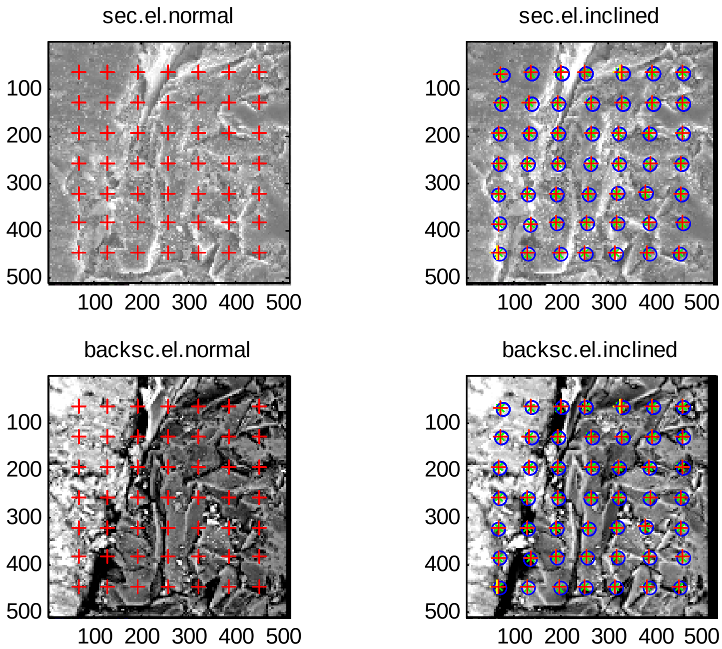

Fig. 5 Example of marked images during disparity analysis (2nd layer) – no need for corrections (though there was not a complete agreement in correspondences, the automatic corrections were sufficient)

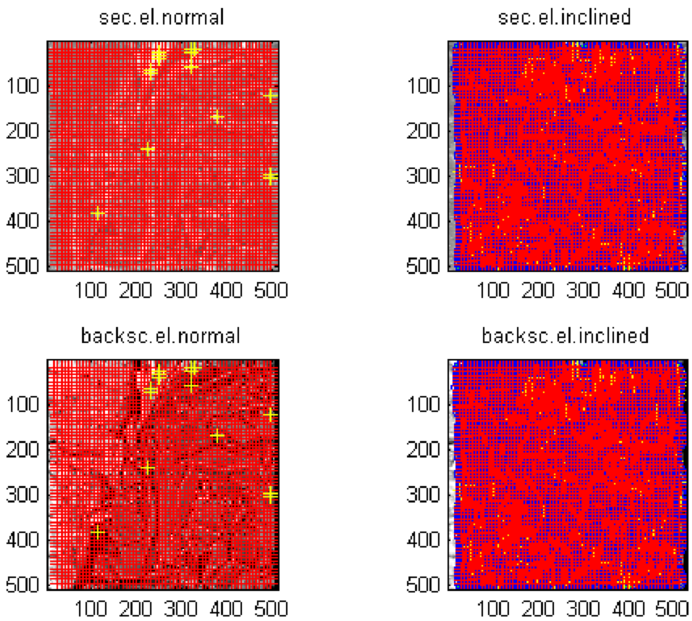

Fig 6 Continuation of previous example: 3rd layer – questionable correspondences marked light

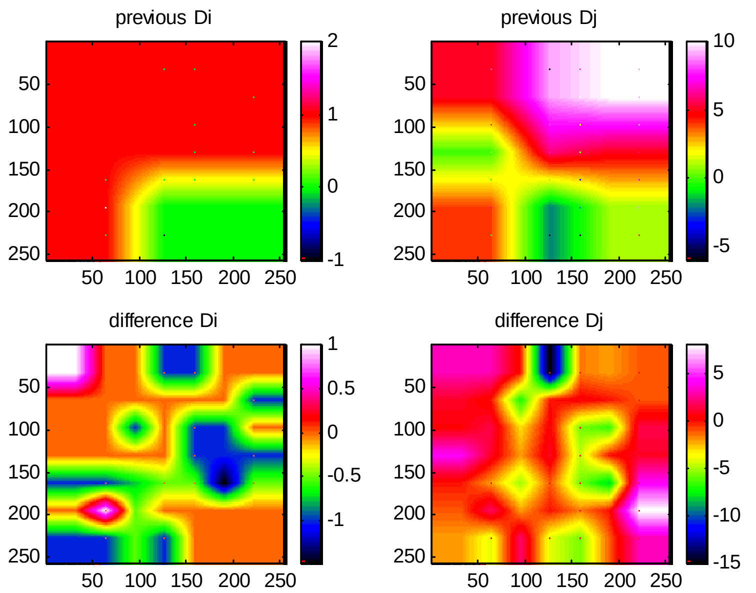

Fig. 7 Disparity estimate after the 1st layer and corrections after the 2nd layer analysis

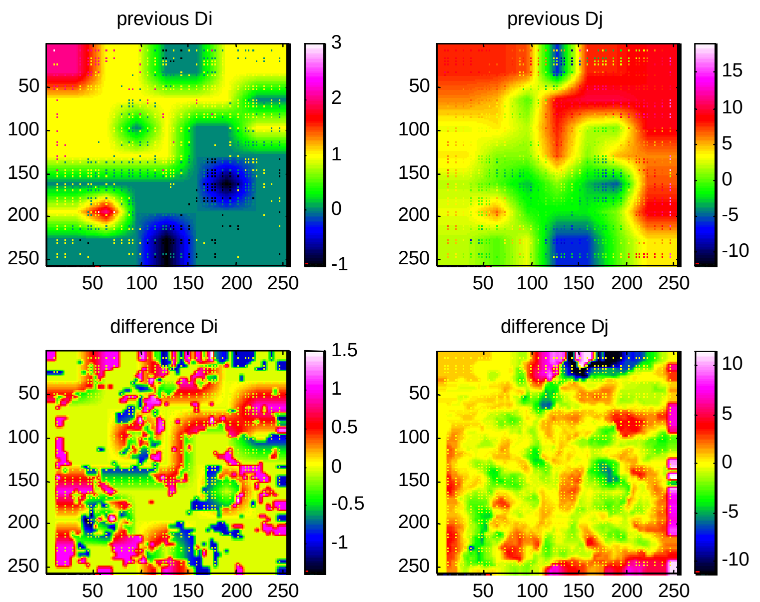

Fig. 8 Disparity estimate after the 2nd layer and corrections after the 3rd layer analysis

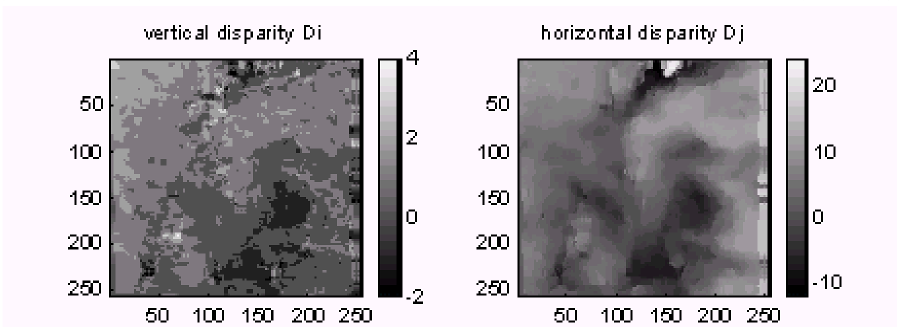

Fig. 9 Final disparities

- Problem of determining the tilt-axis direction, which can be both shifted and rotated with respect to the expected position has been solved by estimation based on the field of space angles φ(p) which is influenced both by the shift and rotation (leading to a circular component in disparities). The procedure consist of the following steps:

- "rectification" of the disparities (angles only in 0 to π range),
- compiling the angle histogram of "rectified" angles,
- smoothing the histogram by a circular convolution with a suitable window,
- determining the direction of $\mathbf{n}$ as the angle corresponding to the maximum of the smoothed histogram.

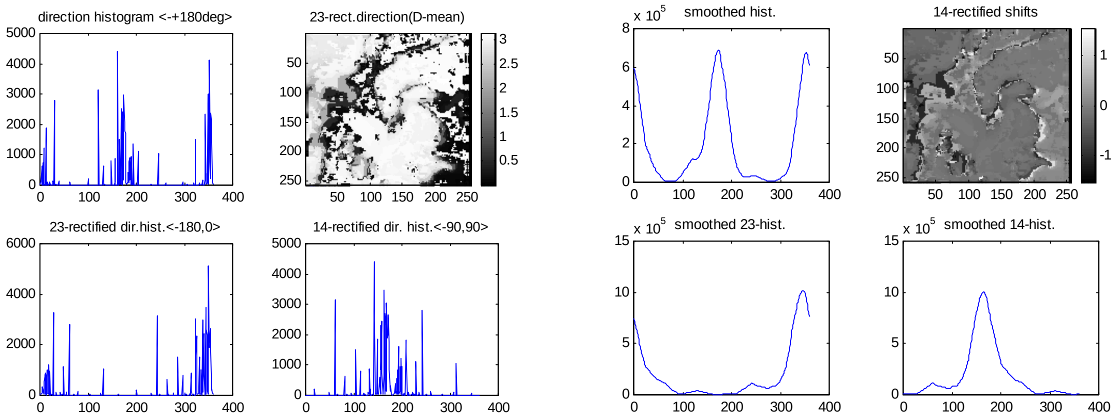

Fig. 10 Example of the raw and smoothed histograms

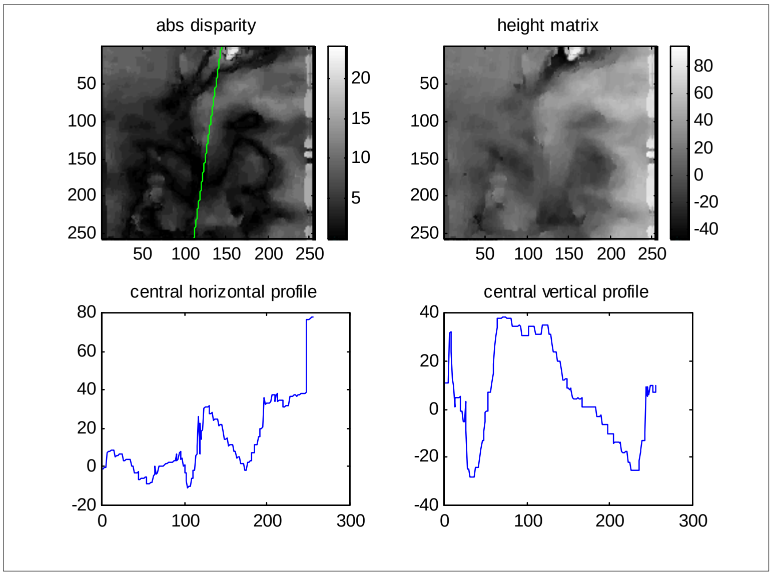

Fig. 11 Disparity matrix with superimposed position of the tilt axis, calculated height matrix and height profiles

- Problem of topology preserving manifests itself as physically impossible "folding" of the resulting disparity map. The prevention is based on the following rule: the disparity map must be topologically correct, i.e. not folded (which implies the proper order of points),

$$\left|\operatorname{grad}\|\mathbf{d}(\mathbf{p})\|\right| < 1, \quad \forall \mathbf{p} \, .$$

Presently, only 1D check (sufficient as the disparities are now sufficiently parallel) is applied. Then, only local check during disparity analysis is needed (thus no complicated global check of the final disparity matrix) and proved effective. This criterion is used as the last correspondence check, which can detect the reversal points being mostly those which have escaped the previous three-criteria checks. Experience shows that this check is mostly sufficient to remove (and possibly correct) almost all the correspondences that remained false after previous checking steps.

Conclusions

The presented approach proved to provide reasonably reliable surface reconstruction, in spite of the fact that as the method was gradually improved, the requirements of final users were increased as well (namely, more complex surfaces appeared on the submitted samples).

The occluded areas still need (and probably will ever need) an initial manual correction of disparity analysis results, if any a-priori constrain should not be imposed on the calculated surfaces.

The software system became practically applicable also thanks to solving the mentioned seemingly marginal problems.

The set of programs implements the method that is probably still one of very few really usable approaches to determination of SEM-sample surfaces.

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