O. Hofmann
P. Navé
Messerschmitt-Bölkow-Blohm GmbH (MBB)
8000 München 80, Federal Republic of Germany
H. Ebner
Lehrstuhl für Photogrammetrie
Technische Universität München
8000 München 2, Federal Republic of Germany

DPS—A Digital Photogrammetric System for Producing Digital Elevation Models and Orthophotos by Means of Linear Array Scanner Imagery

Solid state linear photo sensors, area correlation techniques, and simultaneous adjustment promise automated map making and digital elevation modeling.

Abstract: *A new digital procedure for generating and processing scanner images is presented. The terrain is scanned by an opto-electronic three-line scan camera from aircraft, missiles, or spacecraft. Three linear sensor arrays are arranged in the focal plane of the camera objective perpendicular to the flight course. Each sensor array produces an image strip of the covered terrain according to the push broom principle. Points in the digital elevation model (DEM) to be computed are selected in the middle image strip whose object planes are nearly vertical. The corresponding image points in the other two image strips are determined by area correlation methods. The coordinates of all these image points and a few control points are inserted into a least-squares adjustment for computing the orientation parameters of the camera along its entire flight course and the coordinates of the points of the DEM. Raster plots of orthophotos and stereo orthophotos are produced after the digital rectification of the image strips, utilizing the points of the DEM grid.*

Introduction

The user of remote sensing is primarily interested in the radiative or reflective properties of the objects with which he determines the object classes by means of the well known methods of spectral classification. These data are usually collected by opto-electronic sensors which scan the terrain line by line and produce digitized signals for every picture element. The advantages of this method include

- directly computer compatible data format for storage and computations;
- unlimited and practically instantaneous data transmission;
- precise quantitative measurement of radiometric intensities; and
- measurement of the radiation in spectral bands which are important for remote sensing but not registered by photographic emulsions.

These advantages have to be traded off with a severe

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disadvantage, i.e., the loss of geometrically exact stereo compilation, used in photogrammetry so successfully for many decades, as a consequence of the loss of the central perspective picture geometry present in photographs. This fact was not given much weight in the early days of remote sensing. Gradually, however, one realized that the geometrically correct location of the classified pixels is of fundamental importance and is practically indispensible.

These introductory remarks pertain in principle to every opto-electronic scanning process unless it is of the target scanning type as in a vidicon camera. Both the optical mechanical scanner and the scanning method known under the name of push broom principle are impaired by inherent geometrical distortions. In what follows we will confine ourselves to discussing the problems and their solutions of the push broom method (Figure 1).

A semiconductor sensor array arranged perpendicular to the direction of flight in the focal plane of an objective scans the terrain line by line. The picture elements of one line are sensed simultaneously and stored during one scan cycle (Hofmann, 1982).

The instantaneous position and orientation of the sensor array and, consequently, the geometry of the produced image strip depend on the speed of the carrier, its trajectory in space, and the momentary tilt of the camera. These data are not exactly known, and the image strips reproduced from the unprocessed original raw data are geometrically distorted. Thus, the task presents itself to rectify them.

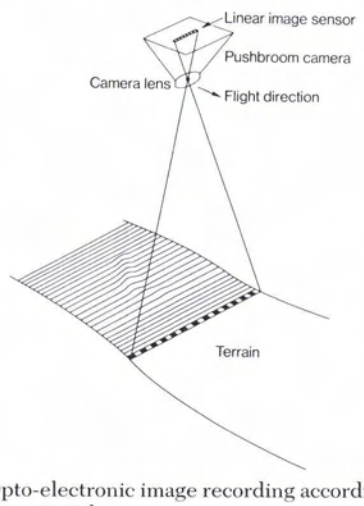

FIG. 1. Opto-electronic image recording according to the push broom principle.

KNOWN SOLUTIONS OF THE PROBLEM

Basically, two methods were developed for solving the problem. One addresses itself to the task of only rectifying the recorded images, the other to determine also the third dimension of the terrain, i.e., its elevations. The latter task can be accomplished in principle only with a minimum of two sensor arrays.

The so-called interpolation method follows a quasi-empirical way. By means of a relatively large number of control points which are approximately evenly distributed over the area to be rectified, the image strip of the scanned terrain is rectified according to certain procedures. To this end it is necessary to identify these control points both in the image strip and in some other geometrically correct representation of the terrain such as a map or an orthophoto, and to measure their coordinates in both representations (Kraus, 1975). It is evident that this is a cumbersome way. The terrain elevations cannot be deduced from the image strips by this method.

The second method consists in either precisely stabilizing or continuously measuring the camera's position and orientation so that both of these are well known along the entire course of the carrier. By arranging several sensor arrays in the focal plane of the objective of the camera, the terrain elevations can also be determined. Although there exist a number of proposals along these lines, e.g., the MAPSAT project of the U.S. Geological Survey (Colvocoresses, 1979; ITEK-Corp., 1981) and STEREOSAT (Welch, 1981), no such method has become operational yet. Both cases deal with satellite-borne stereo push broom scanners. In the MAPSAT project a very precise stabilization and control of the spacecraft is foreseen in order that the pixel traces of the foreward looking detectors coincide with the corresponding pixel traces of the backward looking detectors of the sensor arrays in order to allow one-dimensional epipolar correlation. This concept requires very precise adjustment and absolute accuracy for the camera mounting, and very stringent requirements for the stabilization and control of the satellite's attitude depending on the trajectory and the Earth's rotation. In contrast to this, all these requirements are dispensable for the Digital Photogrammetric System (DPS). It is based on the principle of aerotriangulation and bundle adjustment, whereby a great number of tie points are computed by area correlation. Using these points, the orientation parameters along the flight trajectory and the coordinates of a digital elevation model (DEM) are computed without external informations or measurements. This means that, by analytical photogrammetric methods, the data of orientation and the DEM are computed from the image data alone. Solely for the absolute orientation of the model a few control points are required (as is usual in aerotriangulation).

This procedure is suitable not only for spacecraft but also for aircraft, as all problems of control and stabilization are greatly reduced. The DPS-process

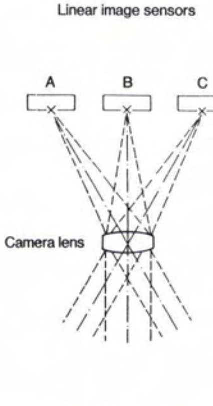

FIG. 2. Three-line camera with only one objective.

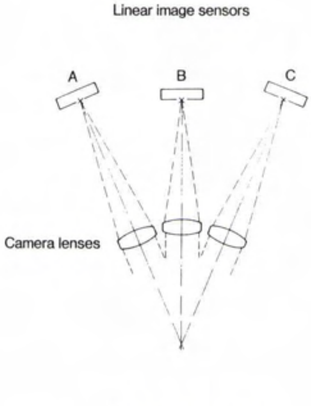

FIG. 3. Three-line camera with convergent objectives.

differs essentially from all existing procedures of geometric rectification of push broom data and brings the digital push broom camera in competition with the photogrammetric camera.

Like the DPS camera described in this paper, the proposed MAPSAT and STEREOSAT cameras are equipped with three sensor arrays, but they use only two of them at a time, either the two outer ones or one outer one and the array in the middle. In contrast to that, the DPS method always uses the image strips of all three sensor arrays. A small but significant difference!

Two earlier propositions should also be mentioned which originated in photogrammetry. In the mid-fifties Rosenberg and Williams published a proposal for an opto-electronic imaging method (Williams and Rosenberg, 1956). It consisted basically in arranging two opto-electronic scanners perpendicular to the direction of flight and one scanner parallel to it. The data of the outer orientation were to be measured continuously. The aim of the scheme was to provide data for electronic processing to produce orthophoto maps.

In 1970 Derenyi published a proposal for a three-channel strip line camera which produced three image strips of different perspectives simultaneously (Derenyi, 1970). He realized that the camera's orientation parameters can be reconstructed from the image coordinates of corresponding picture elements of the image strips. It is strange that this idea was never developed further. The DPS principle was originated independently and without knowledge of the work of Derenyi.

THE PRINCIPLE OF OPERATION OF DPS

The DPS camera contains in the focal plane of an objective three linear semiconductor sensor arrays A, B, and C, which are oriented perpendicular to the direction of flight of the carrier (Figure 2). Their mutual separations determine the stereo base.

In an equivalent arrangement, three individual objectives can be used whose optical axes are convergent and which illuminate three linear sensors mounted perpendicularly to the direction of flight (Figure 3). This arrangement is advantageous with the long focal lengths which are required for imagery from outer space.

During the flight these linear sensor arrays A, B, and C scan the terrain according to the push broom principle with a synchronous image cycle N, thereby producing three overlapping image strips A_s, B_s, C_s of the same terrain but with different perspectives (Figure 4). Because of the movement of the carrier, a different set of orientation parameters (X_N, Y_N, Z_N, ω_N, ϕ_N, κ_N) applies to each image cycle. On the other hand, each terrain point $P_i(X_i, Y_i, Z_i)$ is imaged at three different image cycles N_A, N_B, N_C and corresponding positions on the sensor arrays A, B, C. As the position of the linear arrays within the image plane and the pixel intervals are known, the image coordinates x_A *and* y_A, x_B and y_B, x_C and y_C of any imaged terrain point P_i can be computed in each case.

By using the proposed DPS-procedure, the orientation parameters along the course of flight at discrete points P_j (orientation points) and the three-dimensional coordinates of the terrain points P_i are computed in a coherent, invariant, and rectified model only from the image coordinates. If this is executed in a local coordinate system at any scale, no further external data are required. If the model data are wanted in an absolute general coordinate system, at least three control points are required which have to be identified in the DPS model. For this absolute orientation, orientation parameters of the camera are also suitable. This may be important in those cases where the orientation parameters of a spacecraft over unknown terrain can be determined more easily than control points on the ground.

For the generation of the DPS model, we use the fact that each terrain point is scanned from three different camera positions at three different image cycles N_A, N_B, and N_C. Consequently, there exist three image rays intersecting in that terrain point.

In principle, two algorithms exist for the model computation:

- With the image rays belonging to an identical terrain point, the coplanarity equations are set up. This means that two image rays must be situated in one plane. For each terrain point, normally three coplanarity conditions (three combinations E_AE_B, E_AE_C, E_BE_C of three rays) can be set up. These equations contain only the image coordinates and the orientation parameters.
- For each of the rays E_A, E_B, E_C the collinearity equation is set up. It contains in each case the image coordinates and the orientation parameters as well as the terrain coordinates.

The precondition for both methods is the identification by area correlation of the image points belonging to the same terrain point. In both cases the set-up of error equations and the solution of the corresponding normal equations leads to the desired results.

We have decided to adopt the second method as it allows a straight forward least-squares adjustment for the whole model, including the terrain points. The following explanations therefore refer to that method.

It is not required and practically impossible to compute the coordinates of each terrain pixel and the orientation parameters for each image cycle N. It is sufficient to select discrete terrain points, so called digital elevation model (DEM) points P_i, and to represent the terrain by a network of these points. In a similar way we compute the orientation parameters only in discrete "orientation points" P_j whose intervals depend on the smoothness of the movement of the carrier and the required accuracy. All points within a DEM mesh and all parameters between the orientation points can be determined by linear or non-linear interpolation.

The computation of the DPS model is executed in two steps: At first the image coordinates of the DEM points are determined by area correlation and then the model is computed by the second method (i.e., the collinearity equation).

DATA COLLECTION

The computer selects DEM points in the middle image strip B_s which was produced by the sensor array B. Their corresponding image points in the strips A_S and C_s are determined by area correlation techniques (Figure 5). The computer works step by step from one DEM point to the next so that already correlated and thus identified points can be utilized to extrapolate temporary rectification parameters for improving the geometric similarity between the pixel matrices to be correlated. Similarly, the coordinates of the corresponding image points of the DEM points can be estimated prior to the correlation of the windows surrounding the DEM points, whereby the probability of a successful correlation is improved. This method is well known (Panton, 1978).

The DEM points in image strip B_S are positioned so that the areas to be correlated exhibit sufficient image contrast. For area correlation, besides the well-known cross correlation, a new procedure developed by Pertl and Ackermann (1982) may be used. Window sizes, the determination of the preliminary correlation point, and filtering influence essentially the accuracy and reliability of the results. The point of optimum correlation can be deter-

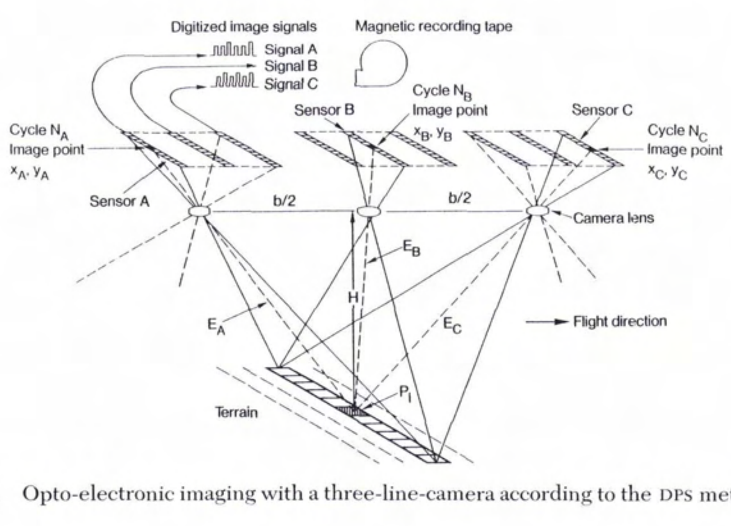

FIG. 4. Opto-electronic imaging with a three-line-camera according to the DPS method.

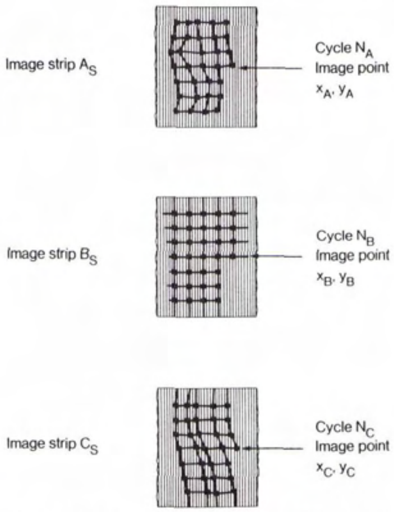

FIG. 5. Corresponding image points of the DEM points in the image strips A_S, B_S, and D_S.

mined with an accuracy of a fraction of one pixel. (Pixel sizes of the CCD sensors used are on the order of 7 to 13 micrometres.)

The following circumstances favor the reliability and accuracy of the correlations: Compared with the correlation of photogrammetric photographs the convergence angle between the image portions of strips B_s and A_s and strips B_s and C_s which are to be correlated are only half as big, i.e., the distortions of inclined surfaces or lines are less by about one half. Both the quality and the modulation of the picture signals are superior to those of scanned photographs. Because of its larger information content, area correlation yields results with greater reliability than correlation along epipolar lines, whose exacting preconditions are not fulfilled in the present case, anyway. The computation time, however, is larger, but fast array processors and skillful correlation strategies (for example, by least-squares adjustment (Ackermann, 1983)) will help to overcome this drawback in a future operational system. Unsuccessful correlations and ambiguities are handled by automatic search processes. For a future operational system, it is planned that in extreme cases of correlation failures an operator can exert his control by means of an interactive stereo video terminal. This stereo monitor system consists of two TV refresh monitors with electronically generated measuring marks, manual controls for the relative motion between the measuring marks and the images, simple stereo viewing optics, and an image memory. Both images may be moved synchronously or relatively to each other by the operator or the computer.

This stereo monitor system would serve to supply the first correlation process, for the identification of control points for the absolute orientation, and last but not least for general supervision and detail evaluation, interactive compilation, and plotting processes.

If they are available, additional distance measurements and orientation data can be provided and may improve the stability and the accuracy.

THE MATHEMATICAL MODEL

The results of the pixel correlations are sets of three image coordinate-pairs each, one pair per sensor array A, B, and C, of a DEM point and the corresponding numbers, N, of the respective read cycles. For half a base length at the beginning and at the ends of strips only two image coordinate pairs are available.

The fundamental geometrical condition imposed is the requirement that the rays through the three corresponding image points and the corresponding perspective centers intersect in the DEM point. This requirement is, as mentioned, implemented by the collinearity equations. They are established for every DEM point and the corresponding image points generated by the sensor arrays A, B, and C. They have the following form:

$$x_{i,N} + v_{x,i,N} = F_x(X_i, Y_i, Z_i, X_N, Y_N, Z_N, \omega_N, \phi_N, \kappa_N)$$
$$y_{i,N} + v_{y,i,N} = F_y(X_i, Y_i, Z_i, X_N, Y_N, Z_N, \omega_N, \phi_N \kappa_N)$$

Here X_i, Y_i, and Z_i are the coordinates of the DEM points to be determined. X_N, Y_N, Z_N, ω_N, ϕ_N, and κ_N are the orientation parameters belonging to the Nth image cycle (N stands for N_A or N_B or N_C) and are expressed by the orientation parameters at neighboring orientation points P_j with indices j.

As the collinearity equations are not in a linear form, they must be linearized by a truncated Taylor's expansion; therefore, approximations for the orientation parameters and the DEM points are required. These data can be determined from the approximately data of the flight trajectory. The approximate DEM points are computed by intersection of the image rays on the basis of the approximate orientation parameters in the cycle number N and the correlated image coordinates.

The image coordinates $x_{i,N}$ and $y_{i,N}$ are considered as observations of a least-squares adjustment and $v_{x,i,N}$ and $v_{y,i,N}$ are the residuals belonging to them.

The observations $x_{i,N}$ and $y_{i,N}$ are complemented by additional observations, e.g., control point coordinates. Neighboring orientation parameters can also be coupled by means of fictitious observations according to a Gauss-Markov-process (Ebner, 1976).

All observations are used in a simultaneous least-squares adjustment to estimate the unknowns. There are two groups of unknowns, the orientation parameters at orientation points P_j (index j, cf. above) and the coordinates of the DEM points P_i. The reduced normal equations containing only the unknown orientation parameters possess band structure and are solved by a direct method.

Insertion of the computed orientation parameters into the normal equations yields the unknowns (X_i, Y_i, Z_i) of the other group. Because of the non-linearity of the problem, several iteration steps are necessary.

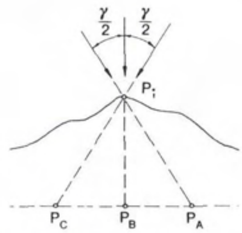

FIG. 6. Principle of ortho and stereo ortho projections.

ACCURACY AND STABILITY

The accuracy of the results depends on the accuracy of the calibration of the DPS camera, on the accuracy of the results of the correlations, and on the inherent error propagation within the DPS strip. The control points establish the absolute orientation, they tend to stabilize the process, and they generally improve the accuracy. But it must be emphasized that the DPS strip is form invariant and stable even without the control points. The inherent error propagation of the DPS strip can be obtained in a well known way from the covariance matrix of the unknowns. The accuracy of the strip results from the superposition of a multitude of individual triangulations and not from the joining of neighboring image lines.

Normally, every DEM point leads to a total of six x,y image coordinates of which three are redundant because determining its own coordinates X,Y,Z requires only three observations. Thus in principle two DEM points suffice to compute the orientation parameters at one orientation point. These are statistical considerations saying nothing about the influence of the location of the DEM points on stability and accuracy of the strip. As a rule, however, many more than only two DEM points per orientation interval are available, producing a large redundancy. Therefore, many correlations can fail before the computation of the strip becomes impossible. Quantitative research into the attainable accuracies will be the predominant part of our future development work.

To prove the feasibility of the DPS procedure, it was checked by a computer generated synthetic model. This consists of a strip of terrain with a length of 3 km and a width of 800 m, and it contains 114 DEM points. By computer simulation, this strip was overflown with a three-line DPS camera, focal length 52 mm, altitude 1000 m. All orientation parameters along the flight path were disturbed by slow sinusoidal oscillations and then the image coordinates of the DEM points on the sensor lines A, B, C were computed.

Then we ignored the given DEM points and orientation parameters and computed these data, i.e., the orientation parameters in 16 orientation points and the coordinates of 114 DEM points. The results revealed the coincidence between the given and the reconstructed model and its stability. (This "normalized" model and its results can be extrapolated by the factor $m_b = H/f$ (flight altitude/focal length) to any operational case.)

FURTHER PROCESSING OF THE IMAGE DATA

By means of the by now computed DEM coordinates and their corresponding image coordinates in the image strips A_s, B_s, C_s, orthophotos and stereo orthophotos can be generated and plotted on a raster plotter or displayed on a video terminal. Geometric rectification is performed within each DEM mesh by parameters which are defined through the four corners of the mesh which are given on the one hand in the image strips A_s, B_s, or C_s and on the other hand in the ground plane.

For orthophoto production, image strip B_s is used. The image coordinates of the DEM points P_i in the strip B_s and their corresponding ground coordinates X, Y in the plan view are known. All picture elements within one DEM mesh formed by their four corner points are to be rectified by projective transformation from the image strip to the plan view. In a similar way the image strips A_s and C_s can be rectified meshwise on the meshes which are formed by the four corner points P_A respectively P_C which are generated by parallel and inclined projection of the DEM points under the convergence angle $\gamma/2$ on to the plan view (Figure 6).

The availability and use of the three image strips A_s, B_s, and C_s for the ortho and the stereo ortho projections enables one to produce representations the distortions of which are minimized, even within each mesh.

The images are now ready for further digital and graphical evaluations such as can be performed on stereo video terminals or on simple parallax measurement equipment.

APPLICATIONS OF DPS

The DPS was developed primarily for rectifying line images. It is therefore only natural to combine the three-line DPS camera with more spectral modules in order to be able to record other spectral bands for remote sensing and spectral classification purposes. Each of these spectral modules consists in principle of an objective with a spectral filter and a line sensor array in its focal plane. The optical axes of these spectral modules are parallel to the optical axis which belongs to the line sensor array B of the stereo module. Also, the sensor arrays are parallel to sensor array B.

With this combined stereo-multispectral push broom scanner, geometrically rectified multispectral images, especially for thematic maps, may be produced in a wide range of scales both from aircraft and spacecraft. The scale depends on the focal length and the flight altitude. DPS can be employed on board any carrier (missile, aircraft, satellite). The carrier's low frequency motions do not effect the accuracy of the process, hence a special stabilization is not required. High frequency motions, however, should be avoided.

In further applications DPS could play a role also in photogrammetry and cartography, particularly for surveying digital terrain models, and for the production of orthophotos and stereo orthophotos. To what extent this will happen will be decided by the general efficiency and the economic aspects of the process, which depend on the achievable computing times, on the investment costs, and on the operating expenditures.

DPS is applicable to a wide range of civil and military cartographic work. Its applications will be preferred in those cases where up-to-date and accurate geometrical and physical terrain data are to be collected automatically over large areas and evaluated in a short time; thus, data transmission in real time is required.

DPS combines the advantages of a correct geometry and photogrammetric compilation and plotting with multispectral digital image processing with all its possibilities.

In the applications mentioned thus far, the emphasis lay on the determination of the geometric shape of the object. Other applications are also thinkable, possibly in real time operations, where the prime aim is the computation of the orientation parameters. Navigational tasks and determining the exact orientation parameters of aircraft and spacecraft come to mind where the DPS camera would act as an orientation sensor which could be coupled to experiments, equipment, and other sensors on board.

Properties, Advantages, and Problems of DPS

The advantages are

- Exact determination of an object's three-dimensional extensions by purely analytical photogrammetric methods. Additional equipment or auxiliary data are not required.
- Homogeneous electronic data processing from the electronic sensor to the end product with only a minimum of interactive controls.
- Homogeneous processing in closed form of arbitrarily long image strips.
- Optimum convergence angle of the stereo images which is independent of the camera's focal length.
- Optimum image data for automatic image correlation.
- Optimum ortho projections, least possible distortions.
- Easy merging of multispectral images.
- The Earth's curvature and rotation, perturbations of the trajectory and attitude, and elevation differences of the terrain do not affect the accuracy of the DPS strip.

The chief problem of DPS is the large quantity of data to be handled, resulting in problems of storage capacity and computation times. A future operational system, however, will be characterized by the computing time reductions realizable with array processors and optimum computer coding. The storage problems may be eased by the advent of optical digital storage media.

The State of Development of DPS

Thus far the project has been supported by inhouse R&D funds of the German aerospace company Messerschmitt-Boelkow-Blohm GmbH (MBB) in Munich. Its basic ideas have been filed in patent applications. The mathematical DPS model has been set up and has been coded. For the first investigation of stability and accuracy, a synthetic strip was successfully processed.

The reliable, accurate, and as far as possible automatic correlation is one of the most important prerequisites for the success of the project. Therefore, correlation techniques were intensively studied. Strips with sufficient pictorial structure can now be correlated without failure, with high reliability and accuracy. The computation times are still high, but novel hardware will drastically reduce them.

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