MULTI-TEMPLET-MATCHING FOR THE AUTOMATION OF PHOTOGRAMMETRIC MEASUREMENTS

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SUMMARY

The algorithm of Multi-Templet-Matching is a matching technique for photogrammetric measurements. It represents the basis for the derivation of digital terrain models but also for the automation of aerotriangulation or the elaboration of orthophotos. An analytical plotter is used for the scanning and for the verification of the matching results. The paper presents the matching algorithms and the computer environment.

KEY WORDS

Automatic height measurement, matching, digital terrain model, scanning of aerial photographs, digital photogrammetry

1. INTRODUCTION

Image correlation and the appropriate digitizing of aerial photographs play a key role for the automation of the photogrammetric working process. If one succeeds in automating the matching of corresponding sections of two aerial photographs, then one can develop procedures allowing a high degree of automation of the photogrammetric restitution. This concerns primarily the derivation of digital terrain models, but such a procedure can also be used as a starting point for the automatic derivation of digital orthophotos, which should play a key role for all planning activities in the near future. Furthermore, digital orthophotos are increasingly used in geo-information systems. If one underlays the vector information on the monitor of a GIS with an orthophoto, then most of the photogrammetric plotting operations can be done directly on the working station. Otherwise, image matching can also be used for the automation of aerial triangulation.

For the last few years, a number of research groups have concentrated their efforts on image matching. However, one gets the impression that only partial results have been achieved. Even if practical solutions are currently offered in close-range photogrammetry and for the correlation of small-scale photographs, only partial solutions are available for large-scale photographs. At the Institute of Photogrammetry of the EPF-Lausanne, a small research group has been heavily engaged for some years in the problem of image matching and close collaboration was achieved with the firm Leica, Unterentfelden. This commitment led to the development of a reliable procedure for image matching, which can also serve as a basis for completely automated aerotriangulation.

One of the key elements for the automation of image restitution is the algorithm for image matching. Moreover, the technique of image digitizing and the instrumental equipment are of the utmost importance. At the very beginning, the Institute experimented with the dynamic programming, which served as a basis for the development of the Multi-Templet-Matching. In a first phase of this algorithm, the parallaxes of square image segments of varying size are determined. These parallaxes of overlapping picture elements are then introduced in an adjustment procedure by which the terrain is approximated by finite elements. The procedure also allows the introduction of break-lines and the incorporation of discontinuities. In this way, the terrain is approximated, including irrelevant objects like houses or trees, which are subsequently largely eliminated by filtering. Finally, the correlation results are verified and edited before integration into a GIS station.

Beside the height parallaxes, the correlation procedure also gives the Y-parallaxes of the picture elements. Consequently, the procedure also supplies the parameters for the computation of a relative orientation. If these elements are taken together for a whole block formation, one can even automate aerotriangulation. These procedures are implemented on the instruments of the Institute of Photogrammetry, where the digitalization is done on an analytical plotter DSR15. A parallel processor based on Transputer technology has been developed for the computer-intensive correlation algorithm; this processing is done independently of the digitalization on the analytical plotter. Subsequently, the results of the image correlation are transferred to the analytical plotter for verification. In this context, the analytical plotter still plays a key role for data processing. However, while it is clear that the analytical plotter could be replaced by a digital plotter for the verification, it is yet not evident that the verification process can be done more efficiently on a digital plotter than on the analytical plotter.

2. DIGITIZING OF AERIAL PHOTOGRAPHS

The quality of the digitalization process is of the utmost importance for automatic image processing. It is essential that the whole range of grey levels of an aerial photograph be converted into a computer-readable form with minimal noise. If not, it is quite impossible to expect from image processing about the same results as from visual photogrammetric measurements.

In a first approach, it does not seem very easy to establish tolerances for the digitizing of aerial photographs. Most logically, one will start to analyse the efficiency of the human eye as visual procedures are well proven

methods for photogrammetric plotting. The eye is able to distinguish only about 10 grey values, whereas a CCD-camera supplies in general 256 grey levels or 8 bits. This direct comparison of the sensitivity of the eye and the number of digits of a CCD-camera is however very biased, as the eye has a great relative sensitivity whereas the sensitivity range for the analog to digital transfer is predefined. That means that the human observer will also be able to distinguish considerable texture, even in an area of poor contrast, whereas the digital camera with its 256 grey levels might already be too insensitive.

If one tries to quantify the radiometric requirements of a digital camera, then it is useful to establish a relation with the photogrammetric characteristics of an aerial photograph. The density range of a black-and-white photograph can be estimated at between 0.1 and 1.5, possibly 2.0 D, whereas color photographs can have a density range from 0.2 to 2.5 D. According to our own investigations, one can state that black-and-white photographs with poor contrast still allow a human observer to distinguish density differences of 0.01 D. Similar figures are obtained with the Weber-Fechner experiment (cf. for example [1]). This sensitivity to the contrast tends to be consistent for a human observer over a large density range and decreases only in strongly blinding or very dark regions.

The sensitivity of a digital cameras is usually proportional to the brightness. If one refers this sensitivity to photometric quantities, one should take account of the transparency. Fig. 1 shows the effective measuring values of a digital camera. One can see that the discretization of 256 grey levels gives a very inhomogeneous resolution; whereas bright areas have a very discriminating definition, rather large steps are obtained in

darker areas. The radiometric resolution being greatly limited by the noise, the noise of the electronic device as well as the noise of the photographic image should be taken into consideration. Reasonably, the noise of the camera should remain beneath the noise of the image. Even the noise of the emulsion is not invariant and can be largely reduced by an appropriate illumination. For example, the noise of the grain of the emulsion is largely amplified by directed light, whereas a surface illumination can largely reduce this effect.

2.1 Image digitalization with the analytical plotter DSR15

For image digitizing, the Institute of Photogrammetry essentially uses the analytical plotter DRS15. Test measurements have also been made on a Perkin-Elmer scanner, on a Hell scanner and on the scanners of Intergraph and Vexel. Due to its flexibility and to the high image quality obtained, preference was given to the analytical plotter DSR15, equipped with a CCD-camera (image matrix 512x512 pixels, image resolution 8x12 microns). The relatively small image sections scanned by frames of only 4x5 mm require the assembly of the images. Furthermore, overlapping surfaces are meaned out.

In order to assure a rather homogeneous sensitivity over the whole image density, the image is scanned with different brightnesses (up to 5x). The camera allows such a procedure as a blinding of neighbouring pixels is avoided by the electronics of the camera. Furthermore, the illumination has been modified by the introduction of a diffuser in order to obtain incoherent light. The mounting of a diffusing sphere would certainly have been more useful, but was not realized for technical reasons.
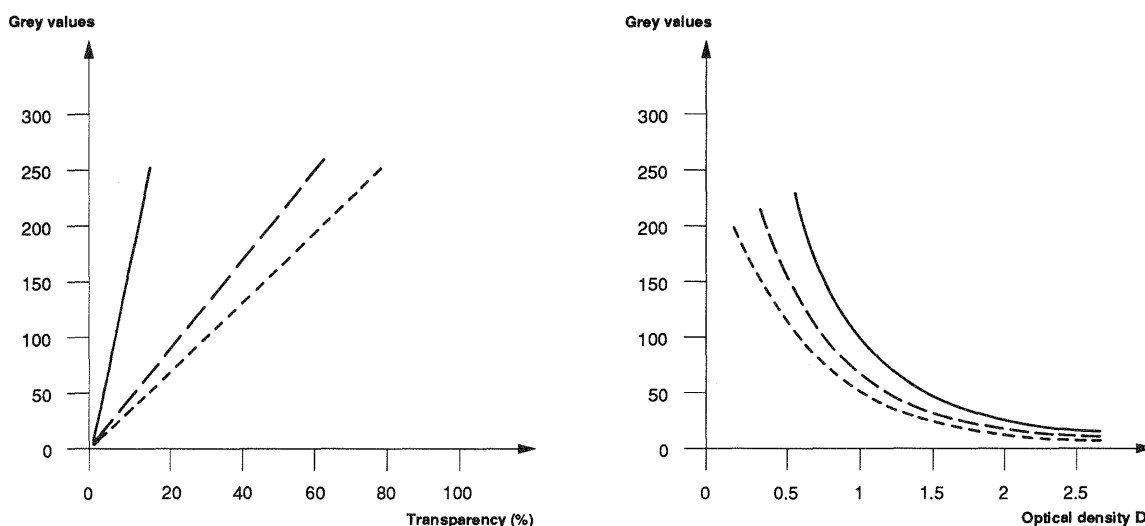

Fig. 1

Sensitivity of the Philips CCD-camera presented in density and transparency. One notices the linear relation between the measured grey density values and the transparency. As far as the density of aerial photographs is concerned, one notices a strong decreasing of the sensitivity in dark regions.

According to control measurements on different aerial photographs, it has been possible to reduce the noise beneath 0.01 density values for a pixel size of 12x12 microns. Otherwise, an homogeneous sensitivity over the whole range of grey values of an aerial photograph has been obtained. In such a way, results have been obtained which, according to our experience, were up to now not possible on other instruments.

3. THE CORRELATION ALGORITHM

3.1 Requirements in the image correlation

Most of the matching algorithms used today require a good image contrast; very often, image segments for image matching are chosen by means of an interest operator. Subsequently, the correlation algorithm is applied to these image segments. A disadvantage of this procedure is that the interest operator is independent for the 2 pictures. The matching is only realized in a second step. In poor contrast areas, this procedure can lead to numerous misjudgements and additional conditions are necessary for reliable image matching. It seems much better to evaluate the quality of image correlation with the help of similarity parameters derived from both photographs. Moreover, it should especially be taken into consideration that areas with poor contrast are very important for height measurements, especially on large-scale photographs. Good contrast conditions are found on houses or trees, which are of no interest for the terrain determination. Areas where the terrain is directly visible are often characterized by poor contrast, as in general in meadows.

Therefore, when developing the correlation algorithm, great emphasis was given to the correlation of image sections with poor contrast. This requires an algorithm which treats large areas. Such a procedure, however, requires iterative solutions with a geometric resampling, as a good coincidence between image sections can only be obtained by also taking into consideration the terrain undulations. Such a sensitive matching algorithm must also correct the possible great differences in grey values between the 2 corresponding images. Furthermore, it is important to also take into consideration the Y-parallaxes, in addition to the X-parallaxes.

3.2 The Multi-Templet-Matching

The above-mentioned requirements led to the development of 'Multi-Templet-Matching'. In a first phase, this procedure treats square image segments called 'templets'. These sections are shifted in the search image (for example right image) and the disparity between the grey values is determined by comparison with the corresponding templets in the left image. The minimum value of the disparity determines the parallax for the corresponding templet. This parallax value is introduced in an adjustment procedure by which the terrain is approximated by finite elements. For this adjustment, the parallaxes represent the observations and the height of the nodes of the finite element structure are the unknowns. In order to obtain fairly smooth surfaces, triangles are used as finite elements and furthermore the change of the slope angle of an adjacent triangle surfaces is also minimized. The finite elements also supply the approximation surfaces for the resampling of the search image. After the geometric transformation of the search image, one repeats the correlation procedure with the templets.

The size of the templets is variable and chosen in an overlapping way according to a quatree structure. The smallest templet has a size of 12x12 pixels, whereas the largest templet measures 400x400 pixels. In this way, a very reliable procedure is obtained, which can also be used for the determination of the Y-parallaxes.

3.3 Determination of break-lines

The terrain approximation with its objects requires a very flexible approximation surface. That means that, in built-up areas and for large-scale photographs, houses, roads, embankments or even trees should also be properly modelled, at least in a first phase. This required flexibility of the finite elements can only be obtained when break-lines and even discontinuities are allowed. On the other hand, these finite elements should have considerable stiffness in areas with poor contrast in order to increase the reliability of image correlation.

As an argument for the automatic determination of break-lines, one can use the grey value changes or the height changes. The work at the Institute of Photogrammetry concentrated on the combination of both variants. In a first phase, the grey values of an aerial photograph are analyzed for significant changes. These changes are determined with the Sobel operator. Subsequently, in all areas detected by the Sobel operator, one computes approximating surfaces to the grey values. The intersection of these approximating surfaces with the mean grey value represents the break-line. According to the size of the approximating surfaces, line elements are obtained which can be immediately used as limits of the elementary surfaces of the finite elements. Various tests have shown that an aerial photograph can be segmented very efficiently in this way (cf. fig. 2). Of course, one obtains in this way numerous lines which are not really break-lines. The subsequent terrain approximation with finite elements must therefore be used in order to verify that all these border lines correspond effectively to considerable changes of the parallax values. If this is not the case, the weighting on the border lines can be changed so that only real height variations remain as break-lines.

3.4 Precision of Multi-Templet-Matching

Although the technique of Multi-Templet-Matching have been tested on several different models, precise numerical results are available for one model only. This test model represents agricultural terrain including a rather extensive village. Ploughed fields with good contrast conditions alternate with meadows with poor contrast; the area is hilly with height differences of about 50 m (picture scale 1:5000, camera principal distance c = 300 mm, flying height 1500 m).

Table 1 and fig. 3 give an overview of the resulting precision. According to this table, a precision higher than 0.1 ‰ of the flying height was obtained in all 8 regions, even when the contrast is very poor.
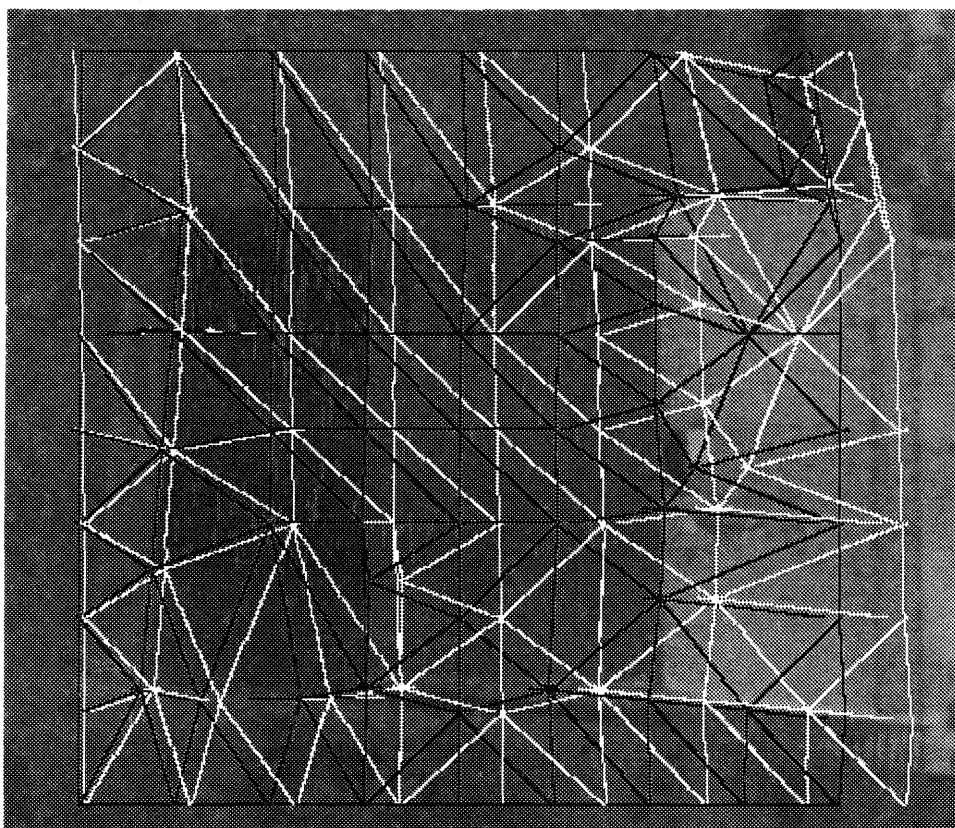
Fig. 2

Network of finite elements superposed on a section of aerial photograph as resulting from automatic correlation by Multi-Templet-Matching. The finite elements are used for the adjustment of the parallaxes determined from the individual templets. The white lines represent the parallaxes and the black ones the basic network of the finite elements. This approach also allows the detection of break-lines and the modelling of houses.

	Control points	Contrast conditions	$\sigma(H)$
Zone 1	460	good contrast	± 7 cm
Zone 2	460	good contrast	± 8 cm
Zone 3	1121	varying contrast	± 13 cm
Zone 4	324	weak contrast	± 7 cm
Zone 5	211	weak contrast	± 13 cm
Zone 6	560	varying contrast	± 11 cm
Zone 7	252	weak contrast	± 11 cm
Zone 8	84	very weak contrast	± 12 cm

Table 1

Results of a precision analysis of Multi-Templet-Matching. The control points were measured on an analytical plotter Wild BC1 with regular grid and a mesh width of 2.5 m.

$\sigma(H)$ gives the standard deviation between the height of the control points and the values derived from Multi-Templet-Matching. Picture scale 1:5000, flying height above ground 1500 m. Fig. 3 gives the location of the 8 test zones.
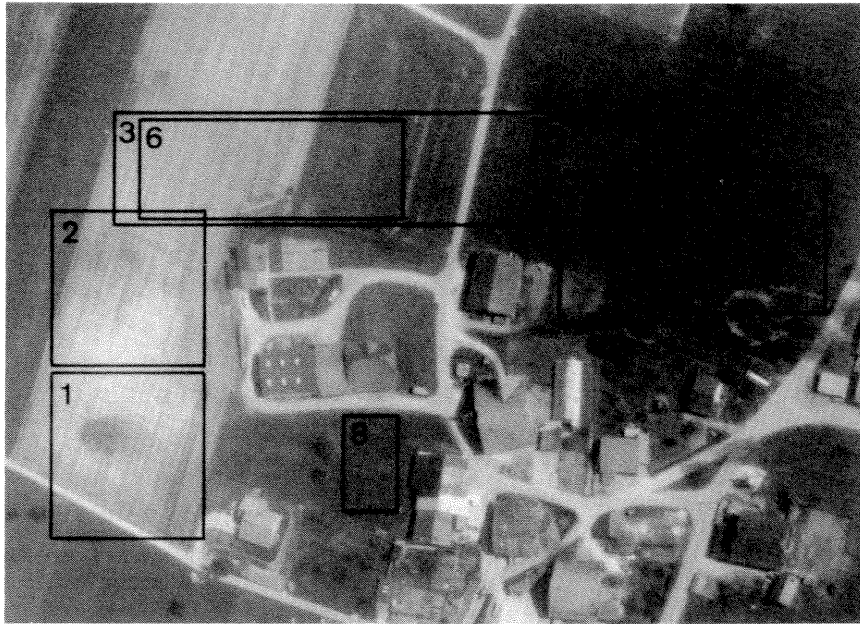
Fig. 3

Photograph showing the 8 different zones used as test areas for precision analysis of Multi-Templet-Matching.

Fig. 4

Contour lines generated from automatic image correlation in a densely built-up area. The contours generated by image correlation (thin lines, 50 cm interval) are compared with operator drawn contour lines (thick lines, 1 m interval); picture scale 1:5000, flying height 1500 m. For technical reasons, the two sets of contour lines are displaced in height by 50 cm.

It is understood that these tests could have been considerably extended, but we got the impression that the real problems do not occur in open areas, for wich most correlation procedures supply quite satisfactory results. Difficulties are however encountered in areas with great slope angles and in the surroundings of terrain obstacles.

3.5 Filtering of terrain obstacles

The procedure was conceived in such a way that the terrain surface with all its objects can be determined with high precision. It is only in a second phase that these objects are then eliminated by appropriate filtering. For this filtering, the node points of the finite elements approximation are once again approximated by finite elements. However, larger approximation surfaces are used in order to eliminate measurements standing out from the surface and corresponding to the measurements on houses or trees. Various practical tests have shown the efficiency of this procedure. Fig. 4 shows that it is possible in this way to construct, in a completely automatical manner, contour lines which only require minor corrections, even in built-up areas.

3.6 Data editing

In a first phase, the results of the image correlation are filtered and smoothed in order to eliminate terrain obstacles completely automatically, insofar as this is possible. It is understood that this process will always remain limited in precision and a visual control of the height data is absolutely necessary. This control can be done most efficiently on a stereoplotter in which a line map is directly superposed onto the aerial photographs in stereo. For this purpose, the Institute of Photogrammetry uses the Leica DSR15 with the Kriss injection system. It is important to present the computed terrain model to the operator as efficiently as possible. In a second phase, he should be able to make corrections and he should see the result of these interventions immediately. The most appropriate aid for data visualization comes from the contour lines. Profiles or grid models are in general too dense and cover a great part of the picture content. Furthermore, it is important that the operator not need to correct every individual point but can intervene for larger surfaces. A program system is currently being developed, which allows the injection of the automatically generated contour lines into the Kriss injection system of the DSR15. The operator can delimitate wrongly correlated regions and replace them by new measurements; regions which has been measured too high can be corrected for a constant value. Furthermore, it is possible to add break-lines. The results also showed that a contour line presentation is easy to control and can be revised in an efficient way (cf. fig. 4). Problems are however encountered in the quasi on-line presentation of the corrections.

4. CONCEPT FOR AN AUTOMATED PHOTOGRAMMETRIC WORKSTATION

The system used for the development of the correlation algorithm was the analytical plotter DSR15, which offers most of the functionality required. This mainly concerns the computer programs for image orientation, the programs for image digitizing and the possibility of control measurements including image injection. Without any doubt, these programs can also be transferred to a digital workstation. However, for quality and productivity, it is not yet clear whether the same efficiency can be obtained as with classical analytical plotters. It might be interesting to discuss below whether it is useful to use an analytical plotter as an automatic working station or rather to opt for a digital station (cf. fig. 5). For this discussion, the following components necessary for an automated photogrammetric workstation have to be taken into consideration :

1. Scanner
2. Image processor with efficient processor
3. Verification system
4. Raster plotter for the output of orthophotos, as a complement

4.1 Scanner

In table 2, an attempt is made to summarize the requirements in a scanner for photogrammetric image processing. The radiometric requirements have already been discussed in chapter 2. The practical work with a Philips CCD-camera on the DSR15 made it clear that this camera only fulfils the requirements in a limited way. Most probably a line scanner would be more efficient and would allow a more rapid image registration (cf. [3]). The expected scanning time of 5-10 min. for a whole aerial photograph might be somewhat difficult to respect. Much longer scanning times are however problematic if one takes into consideration the profitability of digital procedures in comparison to the classical measurements on aerial photographs, especially concerning aerial triangulation and derivation of digital terrain models. The stipulated requirements are very high and might exceed by far the requirements of the printing industry, which has already been using scanners on a routine basis for quite some time. It is however useful to take into consideration that many more images have to be scanned for aerotriangulation than for the production of orthophotos. Furthermore, a much higher resolution is necessary for photogrammetric operations than for the sole production of orthophotos.

4.2 The image processor based on the Transputer slot system

Multi-Templet-Matching requires considerable computer power, as indeed do many other correlation procedures. It would be desirable to have processors with the efficiency of giga flops. Serial processors of this efficiency are still rather expensive. It should however be much easier to obtain such computer power by using parallel processors.

Three years ago, when the project started, it seemed most appropriate to use the Transputer technology for the development of a parallel processor. Transputers are processors which can be easily interconnected. Each processor has 4 communication channels, allowing rapid data transfer between neighbouring processors (about 15 Mbytes/sec). Furthermore, the T800 processor can be equipped with a storage capacity of about 4 Mbytes. In order to take advantage of the rapid data transfer, it seemed appropriate to equip the Transputer
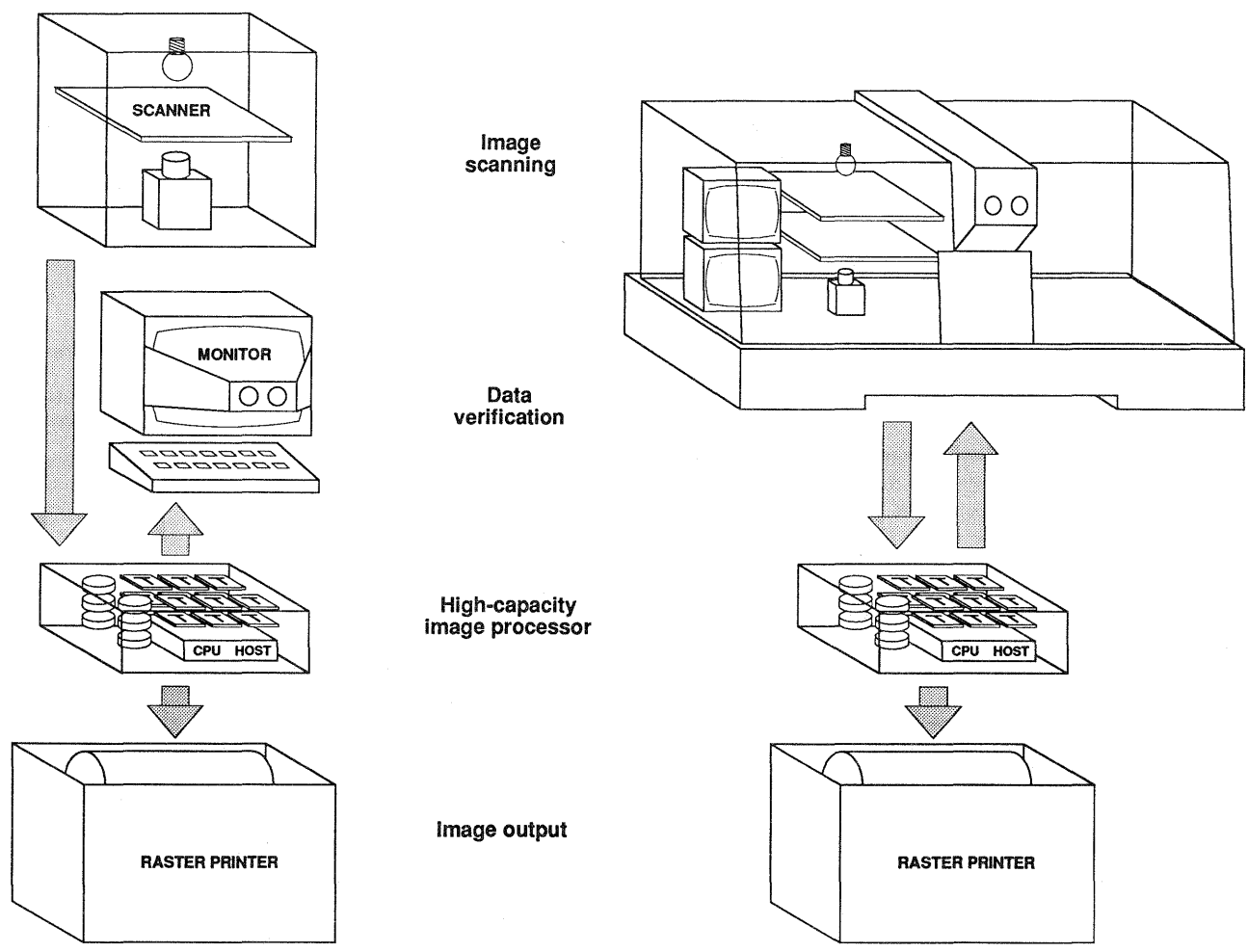
Fig. 5

Components of a photogrammetric image processing system using either a digital workstation (left) or an analytical plotter (right).

Geometric resolution :	up to 10 x 10 μm
Radiometric resolution :	< 0.01 density value
Dynamic range :	0.1 - 2.5 density values
Possibility of scanning black-and-white and color photographs	
Noise :	< 0.01 density value for usual aerial negatives
Scanning time :	less than 5-10 min. for a whole aerial photograph with 10 x 10 μm

Table 2

Requirements in a scanner for photogrammetric image correlation.

with mass storage devices which allow the storage of a whole stereo model. On this base, the Transputer slot system was developed, as schematically shown in fig. 6. It works as a peripheral system in connection with a Vax computer. Currently, 25 Transputers T800 are integrated into the system. All processes of image correlation are implemented on these processors, whereas the determination of the normal equations for the computation of the finite elements is carried out by the host computer. The computer capacity of one Transputer amounts to about 3 Mips and corresponds to the processor power of a Vax processor 3200; the whole system has a 'theoretical' computing power of 75 Mips.
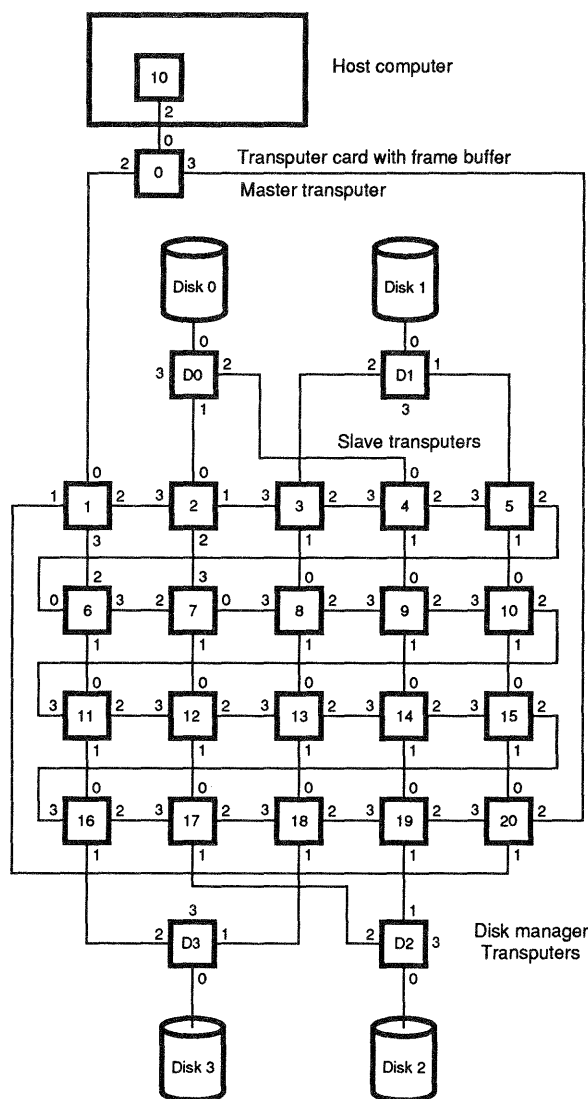

Fig. 6

Configuration of the Transputer Slot System with a distributed mass storage system.

4.3 The verification system

Verification is a very important part of an automated process. The way to control the results of image correlation and of the data editing has already been discussed in paragraph 3.6. This work is currently done on the DSR15, equipped with the image injection system Kriss. In principle, these operations can also be carried out on a digital plotter; however, one may ask if the same efficiency can be obtained as with an analytical plotter. The development work on the injection system has shown that the image definition on a monitor, even with 1'500 x 1'200 pixels, is still considerably lower than in the oculars of an optical system. A rough estimation of the resolution of an optical observation system shows that this corresponds approximately to a performance of 3000 x 3000 pixels, and this being done in stereo. Consequently, the analytical plotter will still play an important role for photogrammetric production, especially when a great amount of data has to be processed.

4.4 Output of image data

An important by-product of digital photogrammetry is the generation of orthophotos. Up to now, orthophotos have been produced on special orthoprojectors, by optical transformation procedures (cf. the Leica OR1 or the Zeiss Orthocomp). The digital processing of data should allow a considerable increase in quality according to the experience of the printing industry. The image could be reproduced on the basis of photographic procedures or on the basis of ink-jet or laser printers. The advantage of ink-jet printers lies in the possibility of reproducing a very limited number of copies. It would then be possible to produce orthophotos on request, whereas photographic procedures are less flexible. Digital reproduction should also considerably facilitate the layout of the orthophotos, including the lettering and eventual cartographic editions.

The large-format raster plotters like those used for color copiers or special ink-jet printers should largely fulfil the quality requirements. The printing time can be considerably longer than the scanning time, as only a limited number of pictures have to be reproduced. The quality of the orthophotos should correspond to a photographic reproduction with an enlargement of about 10 x (cf. table 3).

Image format	A0, possibly A1
Ink-jet or color laser printer	
Resolution	~ 100 points/cm and color with varying point size (equivalent to 1000 dots/inch for a fixed point size)
Printing time for A0	< 30 min.

Table 3.

Requirements in the image output.

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5. CONCLUSIONS

Multi-Templet-Matching represents an efficient method for the automation of photogrammetric image measurements. The modelling of objects and the automatic determination of break-lines allow a high degree of flexibility. The procedure can be used as a basis for the automatic derivation of digital terrain models. Furthermore, it can be used for the automation of image orientation and to a larger extent for completely automatic aerotriangulation. The practical application of this procedure, however, requires different components still in development, such as an appropriate scanner and an efficient image processor. It is therefore interesting to analyze the instrumental environment within which this procedure can be implemented. Many aspects speak for the use of an analytical plotter like the DSR15 or the DS2000 as basic instrument and for an off-line image processing in a special image processor. In principle, an analytical plotter possesses the necessary features for image scanning and a camera can be integrated without great difficulty. However, great care should be taken with the quality of the camera and of the optical system, including the illumination. From this point of view, the time is at hand when all these requirements will be met on a universal photogrammetric measurement system. In an automatic process, the control and eventual editing of the results is also of great importance. For this working phase, an analytical plotter offers numerous advantages. Things are of course different for a research institute, for which the use of components of electronic data processing might be advantageous. From a practical standpoint, the efficiency of a system is of fundamental importance and from this point of view the classical photogrammetric plotters still have great advantages.

REFERENCES

[1] M. Kunt :
'Traitement de l'Information' vol. I : 'Traitement numérique des signaux'
PPUR, Lausanne 1991.

[2] B. Chardonnens, R.D. Hersch, O. Kölbl :
'Transputer Based Distributed Cartographic Image Processing'
Joint Int. Conf. on Vector and Parallel Processing, Zürich 1990 (LNCS 457 Springer Verlag).

[3] 'Solid State Camera Products 1989'
EG+G Retikon, 1989.