MONITORING MARBLE EXTRACTION IN OPEN CAST QUARRIES

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ABSTRACT

Periodic survey of open cast quarries to control the amount of excavated material is necessary for the taxman as well as for planning purposes. This paper reports on the experimental results of automatic DEM generation from aerial images in a marble quarry in Northern Italy. Images of two different flights, 2 years apart, were processed on different DPWs by different processing techniques: image correlation in single models as well as multi-image correlation. The results show a rather poor performance of digital photogrammetry in such a difficult environment, with large dispersions and systematic differences among the DEMs as well as with respect to reference data.

1 INTRODUCTION

1.1 Quarries and DEMs

Two years ago a project was set up whose goal was to investigate the feasibility of using DEMs produced from aerial images on DPWs, to figure out the volume of material excavated in marble quarries: figures on the amount of raw excavated material were required to plan the exploitation of several tens of quarries in the province of Brescia (Northern Italy) by the authorities in charge. Accuracies in the order of 5% of the volume's estimate were deemed acceptable to that purpose.

As far as the choice of the survey technique is concerned, aerial images provide a clear documentation of the *statu quo* at a given epoch, and photogrammetry seemed to be a better solution than topographic surveys. Aerial laser scanning, an obvious and technically better alternative, was at that time ruled out for cost reasons. A 2-years old photographic coverage of an active quarry was available: it was therefore decided to use the quarry as test case and to execute a new flight over the area, to get an estimate of the excavation volumes.

The project goals were set as follows:

1) to select the project parameters optimal for DEM generation (flight plan, image resolution, scanning accuracy, additional terrain information, matching techniques);
2) to study the accuracy of the DEM with respect to different DPW classes.

Details on the DEM of the first flight, included in a single photogrammetric model, and on the planning and execution of the second flight, made of 2 strips, are presented in (Forlani, Pinto, 1999). In the following, after briefly describing the features of a marble quarry which are relevant to DEM generation, the data set and the orientation procedure, the results obtained by using different DPW and applying various processing techniques are presented and discussed.

1.2 DEM generation of a quarry on a DPW

To compute excavation volumes with 5% accuracy, a correspondingly (better) relative accuracy in the measurement of height variations is necessary. Unfortunately, no reliable estimate of the average area and volume extracted over a given time span was available, to figure out the average height changes and therefore the relative accuracy in elevation needed. Rather than fixing an accuracy target value, the objective became to work out the accuracy achievable with the image scale employed in the preceedings photogrammetric surveys (1:5600) with analytical plotters.

From a theoretical standpoint, the overall accuracy of automatic DEMs, expressed by the RMS of the discrepancies between true terrain elevations and their interpolated values from the DEM, may be characterized by three factors (Ackermann, 1996):

- the accuracy in elevation σ_z which depends on image scale m_b, the ratio object distance H to baselenght B and the measurement accuracy in image space σ_p;
- the terrain sampling interval (depending on terrain roughness), gridding method, DEM grid size;
- the detection and filtering of non-terrain features (buildings, trees, etc.).

How may the specific characteristics of a quarry affect the performance of DEM generation algorithms? The marble quarries in the province of Brescia are located in steep hills, with height differences from top to bottom up to 400-600 m; the excavation fronts range from several hundreds meters to more than 1 km. The excavation proceeds in stages, cutting the hill side in banks, slightly inclined downhill, 10 to 30 m high; though more or less you may recognize a main front running parallel to the contour lines, the topography is very rough (Fig. 1). Debris from mine blasting and poor quality material is spread around in several areas, depending on which front is currently active; unpaved roads connecting the different level of the quarry are the only smooth surfaces.

The hills around the quarries are covered by bushes and trees, while the excavation area is rather bright, resulting in a scene with an overall high dynamic range but (though not everywhere) with a low contrast within the quarry, in full daylight and clear sky. Vertical banks cast sharp shadows on the ground.
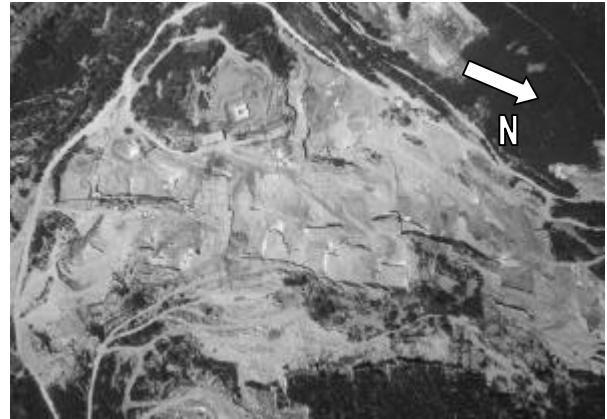

Figure 1. Aerial view of the Botticino quarry

The accuracy of correlation techniques in DEM generation is between 0.1-0.5 pixels. Therefore, increasing image resolution may seem the obvious way to improve measurement accuracy. Noise in photogrammetric scanners, poor image texture in small areas and containing image size to a manageable level limit the practical scanning resolution in the range 20-30 μm: we scanned images at an image resolution of 25 μm. Poorly textured and rough terrain, steep slopes and breaklines, bushes and trees, shadows lead to errors in stereo correlation algorithms: to a various extent, every quarry feature all of them. As image scale and the field angle decrease, their effect is less relevant. Empirical accuracies of automatic DEM generation range from 0.1 to 0.8 of the relative flight altitude (Bacher, 1998; Balsavias and Kaeser, 1998, Duperet, 1995), therefore not (always) matching that of manually produced DEM.

The appropriate sampling size of the terrain has in principle to match the terrain frequency content, based on the sampling theorem. Empirical formulas may be applied based on the average terrain slope; in such terrain most important are breaklines, that should always be included.

Self-diagnosis capabilities in matching as well as in interpolation are necessary to limit editing and improve reliability. Most systems provide a quality index for each matched point, just the correlation coefficient or a somewhat more complex Figure of Merit (FOM): both were found not to be completely reliable, though on average correlated with the errors.

Non-terrain features in the quarry, like cranes, suspension cables, trucks and huts as well as bushes and trees should be filtered out, but (perhaps except trees) they anyway represent a negligible percentage on the volume.

2   TEST BLOCK "BOTTICINO"

2.1   The 1997 and the 1999 blocks

The marble quarry of Botticino, a small village near Brescia, was chosen as the test case, being quite representative of the quarries in the area; height differences from top to bottom are up to 400-500 m, while the excavation front is between 600 and 700 meters long.

The first flight, executed in summer 1997, consists of a single strip with 4 images at the average scale 1:5600 and led to the compilation of a numerical map of the quarry at the scale 1:1000. Although images were taken around midday, sharp shadows are cast from the banks, making sometimes difficult to identify the exact location of the base of the walls. Ground coordinates and the sketches of natural tie points used in the analytical AT of the four images have been made available by Comune di Botticino.

The new flight, in June 1999, consists of two almost parallel strips with 80% overlap and 60% sidelap, in order to derive models with a less favourable height to base ratio, but with smaller perspective distortions, and to reduce occlusions. Since the strips run almost parallel to the excavation front, the lower strip has less occlusions towards the

banks (you can see most of the lower edges of the breaklines, contrary to the higher strip). Using sidelap up to 60% yields four-fold model coverage of the same terrain patch. The advantage here is that each model has a different viewing direction, increasing the possibilities that occluded areas are visible in at least one model.

The 1997 diapositives have been digitized with a DSW 100 scanner, while those of the 1999 with a Vexcel 5000 scanner, both at a resolution of 25 μm.

2.2   Reference data and check procedure

The contour lines file of the 1997 map 1:1000 has also been made available. The accuracy of elevation data, covering a surface of about 1 square km, larger than that of the quarry, may be assumed to range from 20 to 50 cm. Data have been interpolated either by Kriging and by Delaunay triangulation over a 2m grid, to be used to compute the differences with the elevations estimated by the DPWs. To provide a common reference system for the comparison, the ground coordinates of the tie points from the analytical AT of the 1:1000 map have been used.

A second set of reference data was acquired just after the second flight by a topographic survey with a motorized laser scanning theodolite from several stations inside the quarry. It consists of more than 11000 points scattered over an area of about 10 hectares, common to most images of both strips, in the southern part of the quarry. The nominal accuracy is around a few cm in all coordinates but point density is not homogeneous, ranging from 0.25 to 10 points per square meter, due to oclusions.

The procedures devised to asses the accuracy of the DEMs_97 and of the DEMs_99 are different. In the former case, since a massive data set (more than 360000 contour line points) was available, the DEM surface from the interpolated reference data was assumed to be error free and the grid of points generated by the correlation algorithms were interpolated on that. This is in fact only approximately true: predicting the contour lines over the DEM resulted on an interpolation error of 45 cm, more or less the accuracy of the data, with differences up to 10 m located on the breaklines: here, though, the original data do no provide reliable information, since plotting the contours along the almost verticall wall of the banks is not easy.

In the former case, since the area surveyed by laser theodolite is smaller and has an irregular pattern of samples, very dense somewhere and rather sparse elsewhere, it was decided to interpolate the laser points on the surface recovered from the points measured by digital correlation, which were regularly spaced on a grid.

3   TEST ON DEM GENERATION

3.1   Test structure

In order to test differences between different DPWs, either in terms of accuracy as well as in productivity, the same sequence of test has been executed on a top level as well as on a less expensive digital photogrammetric system, hereafter named System A and System B respectively. A third system (System C in the following), recently implemented in house and based on multi-correlation, was also used in the 1999 block, were image redundancy could be exploited.

In a first series of tests, an area of about 320000 square meters, more or less corresponding to the whole quarry, was selected in the 1997 images. A 2 m sampling interval was chosen for System A and a less dense 5 m for System B; both set of values were interpolated over the reference grid. For System B only, DEM generation was supported by providing the system with a coarse DEM, taken from the reference data, in order to find out whether manually measuring a relatively small number of points would improve the result. Details on an intermediate stage of this tests are reported in (Forlani, Pinto, 1999), here just a summary will be given, stressing the new facts.

The second series of tests was performed on the new block. As far as system A is concerned, a DEM with roughly 2 m sampling interval was generated from a 60% overlap model of the lower strip. As far as system B is concerned, an area common to all available models was selected; all DEMs were generated from all available models, comparing the different outcomes. Then, a robustified average value was computed for each elevation. With system C a comparatively smaller area but with a denser spacing was chosen.

In order to make comparison between epochs, all models were absolutely oriented with respect to a set of points in the same reference system. Thanks to the sketches of the natural tie points used in analytical aerial triangulation, most were easily recognized on the two 1997 images. These points are unfortunately no more visible in the 1999 images. Therefore a new set of points, clearly identifiable and common to both epochs, were manually restituted in the 1997 datum and used for the absolute orientation of the 1999 images and of the laser theodolite survey.

System A was running under Windows NT on a PII 400 PC, System B under Windows 98 on a PII 350 PC and System C on a PIII 550 under Linux. Trials on System A were contracted out and only one model for each epoch was generated. System B and C are both installed at the Department, so many trials were possible.

3.2 DEM 97

3.2.1 System A

As mentioned above, DEM_97_A was directly generated in the correct datum, with a grid with 2 m spacing. DEM generation was performed with an adaptive strategy, which determine terrain roughness and changes the matching strategy according to a series of task-dependent pre-defined profiles. No a priori information on the terrain was supplied. The algorithm turned out to be very fast, computing about 10000 points per minute. The values have been compared to the interpolated reference data, resulting in a 2 m RMS, with an average error of 0.7 m (Table 2) and 50% of the differences in the range (-0.5; 0.5) m. As it may be expected, the largest errors occur along the breaklines and in the lower and upper part of the quarry, where there are trees and bushes. Correlations between the errors and FOM values is high.

3.2.2 System B

The same area (but with a mesh size of 5 m in order to contain the computing time) was processed with system B. This system doesn't have predefined or self-adaptive strategies: a seried of trials was executed to find out the appropriate values of the DEM generation parameters available: the correlation window size and correlation coefficient threshold. As far as the former is concerned, the best results were achieved with a relatively large correlation window (14 pixels); small further improvements with a larger windows were not justified by the increase in computing time. As far as the latter is concerned, if the correlation coefficient is lower than the threshold, the program tries again to find a better match starting from an elevation computed from the average of the nearby points; whatever the outcome, the matching value is retained. Indeed, this makes the result not much dependent on the threshold; value of 0.7 was used.

Somehow following the manufacturer suggestion to include some breaklines in such a difficult environment, two low resolution grids, taken from the reference data, were fed to the program to support it in the search for correspondencies along the epipolar line: this is not as effective as actually including the breaklines, but was thought to be a compromise between including a relatively demanding manual measurement stage and no a priori information at all. We used a 50 and a 20 m mesh size, that is about 130 and 800 points respectively; though the solution with a denser grid is better (Table 2), the differences between the two are not proportional to the number of points included. Apparently the system does not constrain its solution to the support grid: errors also appear at grid nodes.

The system output around 13000 points in about 1h 30'. In DEM_97_B we found 8.6 and 7 m RMS for the 50 m and the 20 m grid respectively; large errors (several tens of meters) show up at the border of the area but also inside. Only 14% of the discrepancies are in the range (–0.5; 0.5) m. A plot of the discrepancies show a pattern similar to DEM_97_A; large errors, though, also occur apparently uncorrelated to terrain topography. Very high errors, larger than 100 m, occur along the border of the correlation area.

DEM	# pts	Ave. (m)	RMS (m)	Dzmin (m)	Dzmax (m)	% H_{rel}
DEM_97_A	79536	0.72	2.21	-15.42	30.77	0.2
DEM_97_B (grid 50 m)	12438	0.62	8.60	-147.74	29.47	0.8
DEM_97_B (grid 20 m)	12438	0.53	7.92	-147.74	27.81	0.8

Table 2 – Statistics for DEMs_97

3.3 DEM 99

3.3.1 System A

As mentioned above, only the 60% overlap model of the lower strip was used, thought to have the best viewing angle, as far as the occlusions are concerned, towards the quarry. DEM_99_A was originally generated in model coordinates and later georeferenced with the absolute orientation: the final grid therefore turned out to be a bit denser than 2 m. The performance in terms of computing time was much the same as before. The area covered by the DEM is again about 35 hectares, and was used for a relative comparison with the DEM from System B. The accuracy check is restricted to the 10 hectares covered by the reference data; for some unexplained reason, results are worse, with about 3.1 m RMS (Fig. 3, Table 6) with only 30 % of discrepancies in the range (-1.0 – 1.0) m.

3.3.2 System B

Since one of the objectives of the new flight was to find out whether the availability of a larger number of images could improve the accuracy of the DEM, either by using a multi-image approach or building up a number of DEMs coming from all possible models and nominally referring to the same grid, an extensive series of tests were performed.
The largest area of the quarry common to all images was selected. Then DEMs were created either using 80% overlapping images or 60%, either along or across flight direction, using the matching parameters set up with the 1997 images.

The first comparison was made between the four 80% models and the two 60% models: it turned out that the former are better, even if their theoretical accuracy in elevation should be smaller. The reason is perhaps that the smaller perspective differences help the matching, achieving better correlation values.

A second comparison was made between the 60% models along and across the flight line: those across turned out to be worse, especially along the breaklines parallel to flight direction, were the perspective differences produce occlusions in one of the images of the pair.

Finally, the three models of the upper strip turned out to be better than those of the lower strip, with the largest errors occurring on the banks along the flight line; this is a bit puzzling, because there are less occlusions in the lower strip: may be this is caused by the shadows projected by the walls, which only show up in the lower strip. Fig. 3 shows the differences in elevation between the DEM produced from the lower strip (DEM_B_low) and that produced form the three models of the higher strip (DEM_B_high), overlaid on the contour lines drawn from DEM_99_A. As it can be seen, again the largest disagreement are restricted to the breaklines, while very high differences occur close to the border of the correlation area.
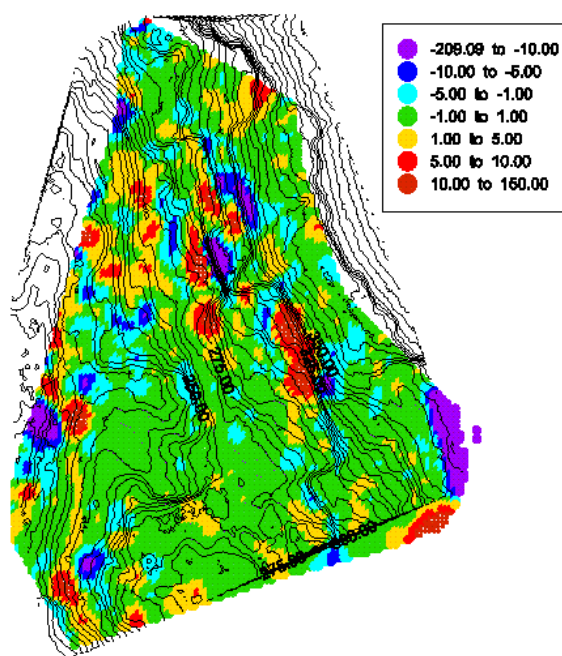

Figure 3. Differences in elevation between DEM_B_low and DEM_B_high

The large differences between single models or strips witness that the result is quite sensitive to the viewing direction With the purpose of getting a more reliable estimate of the height, all 6 models coming from the two strips were combined together: with several elevation data available at each grid node, a weighting problem arise. A simple average would fail in difficult areas, where more than one value may be grossly falsified. Robust estimation methods, handling percentages of outliers as large as 50% would perhaps help; in principle, though, even only one elevation out of the six may be correct. We choose an empirical approach, trying to retain only consistent data set. To this aim, we computed a median value out of the six by taking the 3rd and 4th values of the ordered sample and averaging them on the basis of their correlation coefficient. If there is a consistent subset of data, the median should get it: then an internal quality measure should influence the estimate.
With this filtering of the data, the RMS of the differences with respect to DEM_99_A (taken here as reference, since the area is larger than that surveyed by the laser theodolite) goes down to 3.50 m, with respect to the best result from a single model (RMS = 6.0 m), and much better than the worst (RMS = 18.0 m) which occurred in the lower strip.
Even if the gain with respect to the best model is not striking, the improvement is certainly significant. Restricting the comparison to the area where reference values were available (Fig. 5), show differences quite similar to those obtained by System A on the same data set (Table 6). This suggest that redundancy may, to a certain extent, make up for the poorer quality of the matching algorithms.
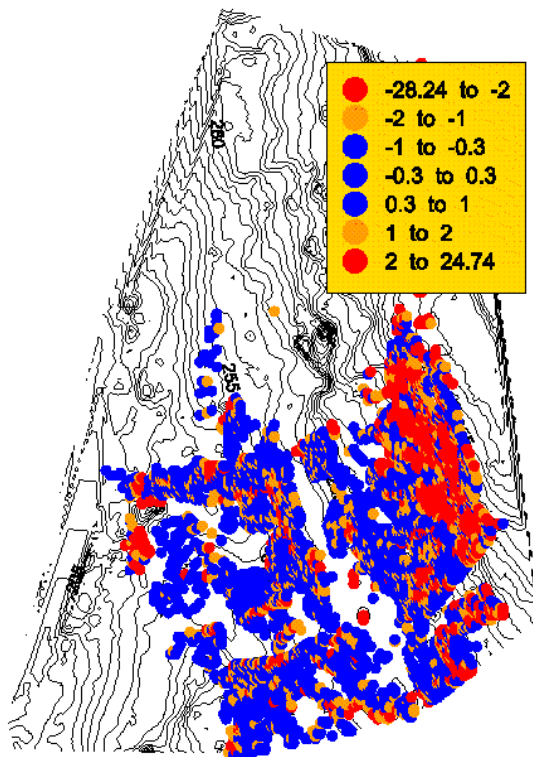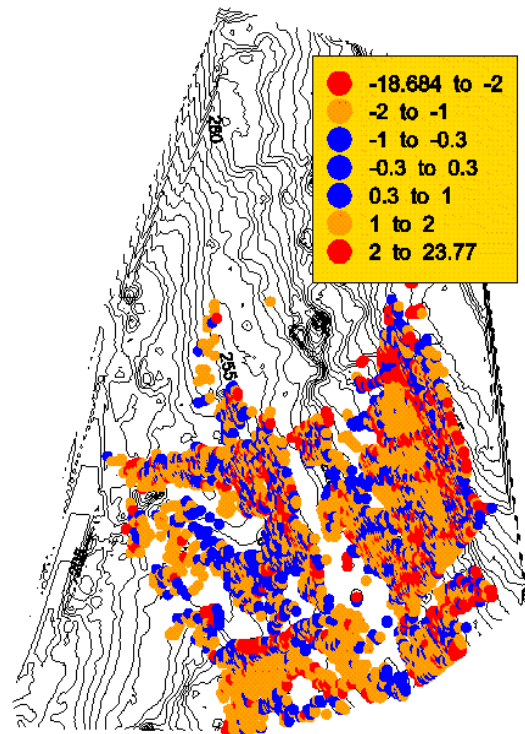
Figure 3. Errors DEM_99_A [m]

Figure 4. Errors DEM_99_B_median [m]

3.3.3 System C

System C is built around a slightly modified version of the MGCM algorithm (Gruen et Baltsavias, 1985) and should in principle increase the reliability of the matching by finding a solution geometrically consistent, more robust with respect to occlusions. The version of the matching algorithm implemented, based on an affine model, does not check for correlations between transformation parameters and this may lead to distorsions of the estimates.

Besides, the program has just been completed and no optimization in terms of performance is available: in this example, with 6 images, it only output 1000 points per hours! Accounting for this limits but to exploit its potential and to compare its performance against the robustified average of the six models of System B, it has been applied to an area of about 5 hectares, which is common to all models. Roughly 11000 with a correlation larger than 0.6, rather evenly distributed on the areas, where determined. The discrepancies with respect to the reference data amount to 3.5 m RMS (Fig. 5 and Table 6).
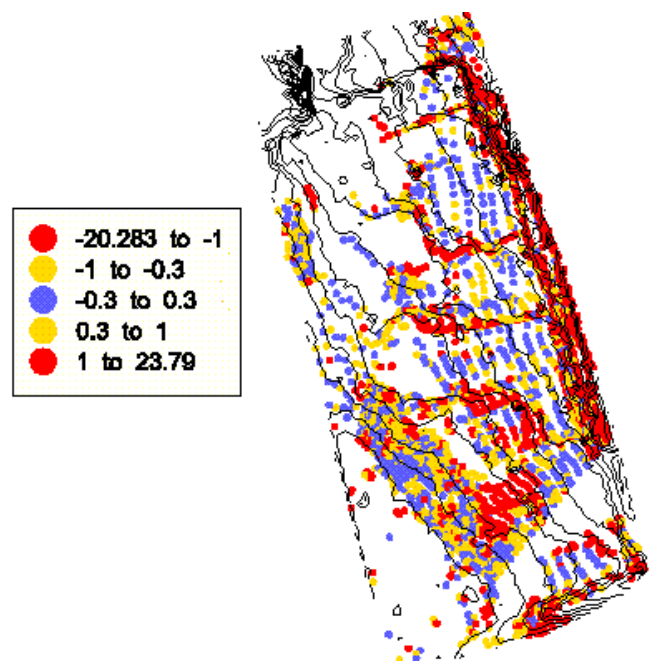

Figure 5. Plot of the discrepancies DEM_99_C

System	# pts	Ave. (m)	RMS (m)	% H$_{rel}$
A	11732	0.97	3.11	0.4
B median	8775	0.33	4.40	0.5
C	6604	0.53	3.53	0.4

Table 6 – Statistics for DEM_99

4   CONCLUSIONS

Automatic DEM generation has been perhaps stretched to do its best in a so demanding terrain. The results obtained in this test, either on top level or in less expensive digital workstation do not match the figures published (though mostly on less difficult environment); the relative accuracy is about 0.36% of the relative flight height, that between 5 to ten times reported figures. Checking the accuracy of the data in this terrain is however a bit tricky: interpolation erros also adds up to discrepancies, since a very dense grid should be used close to the breaklines. Plotting the spatial distribution of the errors clearly show that they are larger on the terrain discontinuities, where (at least for DEM_97) the reliability of the reference values is smaller. As far as DEM_99 is concerned, many points are surveyed at different heights more or less on the same vertical line: again, to remove this effect, a dense grid of points should be measured on the breaklines. This suggest true accuracy figures may in fact me a bit better, but we cannot expect dramatic changes: as far as the objective of this investigation are concerned, digital photogrammetry, though less expensive, cannot cope with the accuracy demand.

A second, perhaps obvious, conclusion is that redundancy may, to a certain extent, make up for the poorer quality of the matching algorithms. Whether this solution is economically acceptable, in the case at hand, is not much on the additional cost of the flight (the quarries are not that close to each other that a single block might conveniently include them all, so single models or single small block must be flown), but rather in the longer computing time and perhaps the complexity of block adjustment. While obvious reduction will be gained by better processors, improvement in the AAT may nevertheless scale down the second problem: in (Forlani et al, 2000) it is shown that the Botticino '99 block has been triangulated by an AAT program.

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