

Aerotriangulation and DEM/Orthophoto Generation from High-Resolution Still-Video Imagery

On the Potential of Digital Cameras Onboard an Aircraft

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Abstract

High-resolution solid-state sensor matrix cameras have found quite some interest among photogrammetrists in the last few years. The limited resolution of such cameras has so far restricted their practical use to applications in digital close-range photogrammetry. Nevertheless, the advantages of the direct acquisition and processing of digital image data in combination with the accuracy potential and the increasing resolution of solid-state sensors have started to make digital cameras interesting for a number of applications in aerial photogrammetry.

This paper presents two practical studies on the helicopter-based use of a high-resolution digital still-video camera for digital aerotriangulation and the automatic generation of digital elevation models and orthophotos. Test regions were an alpine village and a landslide area in Switzerland. The current performance and future developments of solid-state matrix sensors are shown, and the advantages and disadvantages of the use of digital cameras in aerial applications are discussed. Using self-calibration techniques, externally verified accuracies of 2 cm for planimetry coordinates and 5 to 6 cm for height coordinates were obtained in digital aerotriangulation using imagery of 1:20,000 scale, and a precision of 0.03 percent of the flying height above ground could be achieved for digital elevation models.

Introduction

During the past several years, the use of solid-state cameras has found its way into practical applications in close-range photogrammetry. Especially in the use of photogrammetry for industrial measurement tasks, conventional film-based systems can today be considered an exception. The advantages of the acquisition and processing of digital image data (automation potential, direct dataflow with on-line or realtime processing possibilities, high accuracy potential, good radiometric characteristics, and inexpensive system components) suggested this transition from analog to digital as soon as sensors of sufficient resolution and computer platforms of sufficient memory and processing power were available on the market.

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In aerial photogrammetry, the situation is rather different. Digital photogrammetry has been accepted in practice, especially for automatic digital elevation model and orthophoto generation, but digital image data are usually acquired by scanning large-format film. The reason for this is the limited resolution of solid-state sensors. CCD cameras with resolutions of up to 3000 by 2000 pixels are commercially available today, cameras with up to 4000 by 4000 pixels are coming onto the market now, and sensors with up to 9000 by 7000 pixels are currently under development. Linear-array sensors are available at resolutions of up to 12,000 pixels, but require special external control for orientation. This resolution of solid-state imagers is still not comparable to the resolution of standard (23- by 23-cm) aerial film, which can be scanned at resolutions down to 3 μ m. Therefore, film-based systems will prevail in aerial applications for a long time to come.

Nevertheless, due to the above mentioned advantages, the use of CCD sensors is already of interest for a number of special applications. A number of authors have reported test applications of solid-state cameras from aerial platforms for different purposes in the past (e.g., Maggio and Baker, 1988; Novak, 1992; King, 1992; Thom and Jurvillier, 1993; King *et al.*, 1994; Fraser and Shortis, 1995; Kersten, 1996; Abdullah, 1996; Mills *et al.*, 1996), but the consequent exploitation of the accuracy potential of CCD sensors for aerotriangulation and digital terrain model generation has not yet been attempted. Therefore, two pilot studies on the helicopter-based use of a high-resolution still-video camera for digital aerotriangulation and DEM/orthophoto generation were conducted by the Institute of Geodesy and Photogrammetry, ETH Zurich.

Available Sensors

Since the appearance of the first solid-state cameras in the late 1970s, which had only a very limited resolution, there has been a slow but steady growth in the resolution of sensors, with 3000- by 2000-pixel cameras being commercially available today. Major limitations to much higher resolutions are placed by both technical and economic constraints. It is estimated that the production cost of CCD sensors grows with the fifth power of the area of the sensor; on the other hand,

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TABLE 1. DCS200MI - TECHNICAL DATA

| | |
|----------------|--|
| camera body: | Nikon 8008s |
| sensor: | 1524 × 1012 full frame CCD 14 mm × 9.3 mm, black-and-white |
| frame grabber: | in camera body |
| storage: | 50 images, uncompressed, on harddisk in camera body |
| interface: | SCSI port |
| software: | Adobe Photoshop (Mac) Photostyler (PC) |
| weight: | 1.7 kg |
| power supply: | AC adaptor/charger |
| lens mount: | Nikon bayonet |
| lens: | Nikkor 18mm |

pixel size cannot be arbitrarily reduced due to the light sensitivity characteristics of silicon. Moreover, the mass market is currently only interested in CCIR or NTSC videonorm image sensors with resolutions of approximately 760 by 570/480 pixels. Nevertheless, there is a growing interest in high-resolution, solid-state sensors for applications in industrial measurement, science, medicine, graphics, and several other fields. The following list gives a brief overview of the current status of high-resolution CCD cameras in 1996:

- Probably the most widely used high-resolution camera in photogrammetry is the Kodak DCS460 still-video camera with 3060 by 2036 pixels and its predecessors DCS200/420 with 1524 by 1012 pixels.
- Cameras with a 2048- by 2048-pixel resolution are available from a number of manufacturers (Dalsa, EG&G, Kodak, Leaf,

Leica/GSI, Loral Fairchild, Photometrics, Rollei, Thomson, a.o.).

- A prototype of a 4096- by 4096-pixel sensor with a 7.5- μ m pixel size, 6,000 e^- pixel capacity, and a read-out time of 18 seconds was introduced by Loral Fairchild in 1993. Thom and Jurvillier (1993) reported several problems in an application of the sensor onboard an airplane. Recently, new 4096- by 4096-pixel sensors from Kodak and Loral Fairchild with more promising specifications have come onto the market, but have not yet been tested in practical photogrammetric applications.
- A 5120 by 5120 sensor was announced by Dalsa in 1993 (Janesick, 1993), but has obviously never been commercially available.
- A 9216- by 7168-pixel sensor has been developed by Philips, but cannot be considered ready for practical use yet.

For the pilot studies described in this report, we used a Kodak DCS200 (see Table 1), which was operated hand-held from a helicopter (Figure 1). A disadvantage of the camera, besides the limited resolution of only 1524 by 1012 pixels, is the relatively slow data transfer rate, requiring relatively slow aircraft velocities. This disadvantage is aggravated when, e.g., a 3060- by 2036-pixel DCS460 with a storage time of 8 seconds per image is being used. For this reason, and also due to the rigidity of the camera body, a still-video camera can only be considered a compromise onboard an aircraft. For professional use, machine-vision type CCD cameras with rigid bodies and data rates of up to 30MB/sec, connected to an onboard host computer with realtime image display and fast disk arrays, are certainly more appropriate.

A general advantage of solid-state imagery over scanned film is the accuracy potential of the sensors. In close-range applications with signalized targets, well-defined edges or good texture on flat surfaces, precisions in the order of 1/50 of a pixel ($\sim 0.2 \mu$ m) in image space can be regularly achieved, translating into relative accuracies better than 1:100,000 in object space. Also, the radiometric performance of CCD sensors is often significantly better as compared to scanned film.

Test Areas and Data Acquisition

Two test areas were chosen for the pilot studies. The first area was an alpine village (Figure 2), where the use of digital photogrammetry may be interesting for cadastral applications and for orthophoto generation. The second area was a landslide area (Figure 3), with our aims focusing on deformation measurement and DTM generation.

The datasets were first interactively triangulated using both signalized control points and natural tie points. Based on the orientation parameters of the aerotriangulation, digital surface models were then automatically determined from the datasets, and orthophoto mosaics were derived for the two regions.

Urmein — An Alpine Village

The project Urmein consists of a village with an area of 520 by 500 m and an elevation range of 130 m. A total of 50 images (disk capacity of the DCS200) was acquired for the pilot study. The total time for the flight was approximately 30 minutes (Kersten, 1996). The flying height above ground was 350 m, resulting in an average image scale of 1:18,000 corresponding to a ground pixel size of 16 cm. The average overlap was 70 percent in both directions, with large deviations due to handling difficulties with the hand-held camera in the unsteady helicopter. Thirty-six points were signalized with 75-cm white plastic plates. Reference coordinates of these points for an external accuracy check were determined by kinematic differential GPS. The size of the targets touches a general problem of digital photogrammetry: Subpixel resolution with signalized points can only be achieved with super-



Figure 1. Hand-held use of a still-video camera in a helicopter.



Figure 2. Overview image of Urmein.

pixel targets covering at least an area of 3 by 3 or 4 by 4 pixels in image space, thus requiring rather big targets.

Talegnas — A Landslide Area

The project Talegnas depicts a landslide area consisting of lightly forested meadows over a steep rock slope. A number of cracks have occurred in the area during the past years, making regular observations advisable. For the pilot study on the applicability of digital photogrammetry for deformation measurements, 64 points were signalized with 60-cm plastic plates over a 400- by 300-m area with a 160-m elevation range. A total of 35 images were acquired from a helicopter at a flying height of 290 m above ground, which corresponds to an average image scale of 1:16,000. The average overlap was 65 percent in both directions (Frueh and Bernasconi, 1995). Reference coordinates of the signalized points were available from GPS measurements.

Semi-Automatic Digital Aerotriangulation

Both datasets were triangulated using the available signalized control points and additionally measured natural tie points. It was decided not to use automatic point transfer techniques for aerotriangulation due to the irregular flight pattern of the helicopter, the lack of helicopter navigation data, and the deviations of the optical axis of the hand-held camera from the vertical. Thus, control and tie points had to be interactively identified by an operator and then automatically measured with subpixel accuracy by least-squares template matching. Then, a bundle adjustment was performed, introducing some additional parameters for simultaneous calibration. The results of the adjustment are summarized in Table 2.

Although not exceptionally good (the relative planimetric accuracy is only on the order of 1:25,000, while accuracies better than 1:100,000 have been achieved in close-range photogrammetry), the results did basically fulfill our expectations. An externally checked accuracy of approximately 2 cm for the planimetry coordinates and 5 to 6 cm for height were

achieved in both projects. Furthermore, the following conclusions can be drawn from Table 2:

- The results are positively influenced by the large number of signalized tie points, which could be measured in multiple images (points were measured in an average of 5 and 7 images and a maximum of 21 and 15 images, respectively, in the two projects).
- The standard deviation of unit weight $\hat{\sigma}_0$ in the two projects was 0.7 and 0.8 μm , respectively, ($\sim 1/12$ pixel) when self-calibration was used. This is by almost a factor of three worse than the results which are usually achieved in close-range photogrammetry using signalized points and the same type of camera. However, one must consider that signalized points and natural tie points in aerial applications cannot be compared to optimal targeting in close-range applications due to the contrast situation and influences of local terrain unflatness or soil coverage. Nevertheless, these accuracies are significantly better than the results typically achieved with scanned imagery.
- The results of the project Talegnas with self-calibration show a significant improvement over the results with pre-calibration, using a camera parameter set derived from imagery of a testfield taken beforehand. This was to be expected as the DCS cannot be considered a metric camera.
- The discrepancy between interior precision and the RMS of coordinate differences derived from check points in the Talegnas project is obvious. In fact, the network geometry was not very suitable for self-calibration, and the results are characterized by relatively high correlations between parameters. In addition, it is possible that the interior orientation of the camera had not been stable during the flight, an effect which the DCS camera series is known for and which may cause systematic errors (Gruen *et al.*, 1995).

As an additional external accuracy check, 17 distances across the cracks in the Talegnas area, which had been measured geodetically, were compared with distances derived from the photogrammetrically determined coordinates. The comparison yielded an RMS deviation of 13 mm and does thus confirm the above listed results. More detailed results for the Urmein project are presented in Kersten (1996).

The problem of the internal stability of the camera can certainly be solved when a CCD camera is being installed in an aircraft for real production purposes. Crucial for the quality of results is the achievement of subpixel accuracy in the matching process. Especially if area-based matching techniques are being used in large scale applications, the preci-



Figure 3. Talegnas land slide - overview image.

TABLE 2. BUNDLE RESULTS

| Project | control points | tie points | check points | avg. # of rays | $\hat{\sigma}_0$ [μm] | Precision from adjustment [mm] | | | Accuracy from check points [mm] | | |
|-----------------------------|----------------|------------|--------------|----------------|------------------------------------|--------------------------------|------------|------------|---------------------------------|---------|---------|
| | | | | | | σ_x | σ_y | σ_z | μ_x | μ_y | μ_z |
| Urmein (self calibration) | 5 | 112 | 31 | 4.9 | 0.7 | 16 | 17 | 64 | 23 | 18 | 47 |
| Talegnas (pre-calibrated) | 5 | 70 | 61 | 6.9 | 1.0 | 13 | 11 | 53 | 27 | 31 | 108 |
| Talegnas (self calibration) | 5 | 70 | 61 | 6.9 | 0.8 | 14 | 13 | 50 | 18 | 28 | 64 |

sion will depend highly on local terrain unflatness or soil coverage. This will have to be compensated by a careful selection of tie points or by a scheme based on a very large number of tie points, as is often the case in automatic aerotriangulation packages.

Automatic Digital Surface Model and Orthophoto Generation

Based on the results of aerotriangulation, digital surface models (DSMs) were derived from the two datasets. For the determination of the DSMs, the technique of multi-image, feature-based matching, as described in Maas (1996), was applied. The technique is characterized by the fact that no approximate values and no assumptions regarding the maxi-

mum terrain slope are required, and by its high reliability. In a first step, an interest operator (Foerstner, 1986) was applied to all images, extracting discrete points. After this, multi-image correspondences were established using epipolar lines, and ambiguities were solved for by a consequent exploitation of the multi-image geometry. The technique requires each point to be imaged and detected in more than two images (good experiences for this type of terrain were made when requiring each point to be detected in five images). A regular grid was interpolated into the thus determined irregularly distributed 3D points using a Delaunay triangulation based DTM package. Finally, orthophoto mosaics were computed for the two regions.

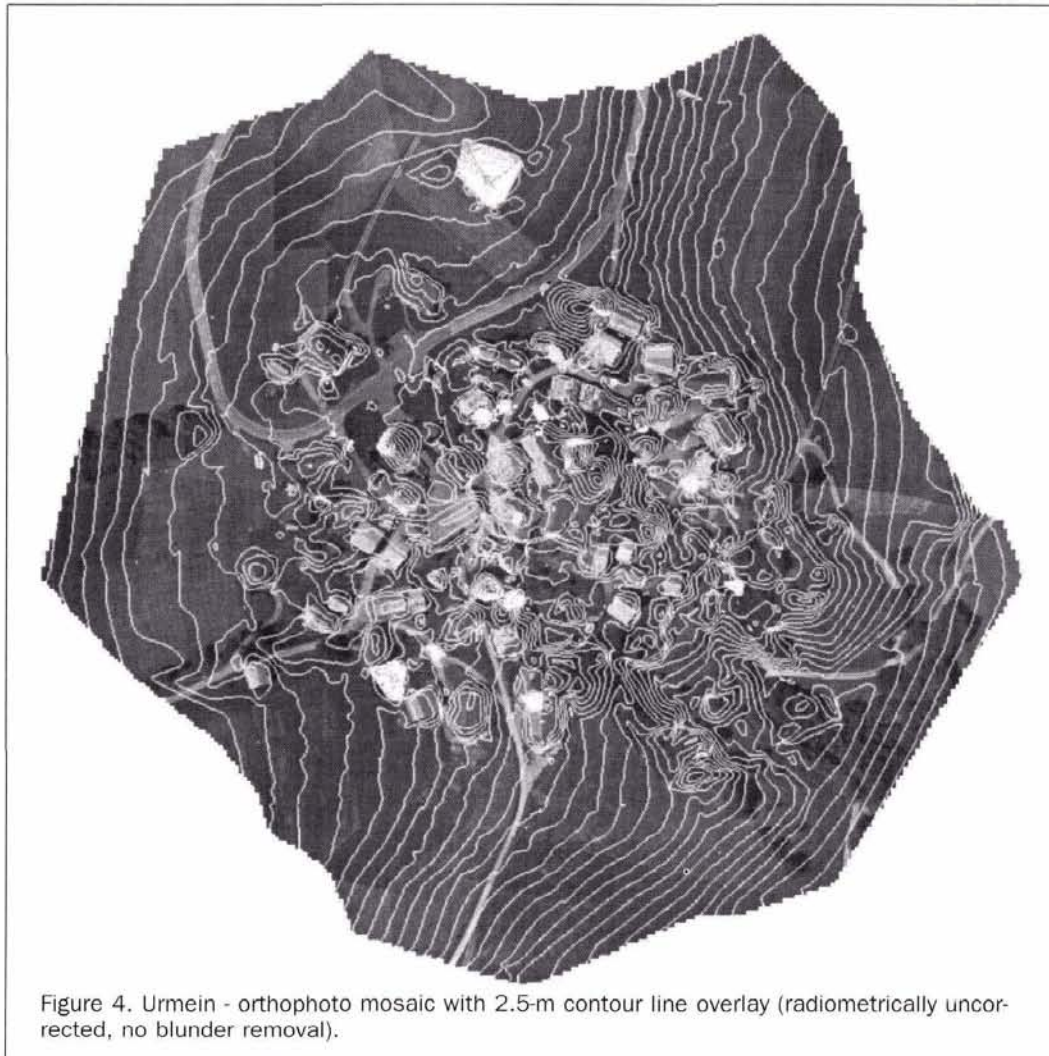


Figure 4. Urmein - orthophoto mosaic with 2.5-m contour line overlay (radiometrically uncorrected, no blunder removal).

Dataset Urmein

Applying the interest operator, an average of 7000 points per image was extracted. Due to the quality of the image and orientation data, a maximum tolerance of 10 μm (~ 1 pixel) to the epipolar line was found to be appropriate for the acceptance of possible matches. Applying the epipolar line intersection routine with the requirement that each point has to be matched in at least five images, a total of 6866 object points could be reconstructed. The maximum number of images in which a single point was successfully matched was 21. The average standard deviation of the reconstructed points was 0.027, 0.027, and 0.109 m in X, Y, and Z, respectively, which corresponds to 0.03 percent of the flying height above ground (Maas, 1996).

Figure 4 shows an orthophoto mosaic with a 2.5-m contour-line overlay based on the raw DSM data without any post processing, filtering, or blunder removal. A thorough visual check of the digital orthophoto mosaic with an overlay of matched points and contour lines showed a total of 12 gross errors in the point cloud, which corresponds to an error rate of only 0.2 percent. Some problematic regions inside the village are shown in Figure 5. Because no information on buildings, trees, etc., was *a priori* given or explicitly extracted by the technique, a large number of successfully matched points are not situated on the terrain surface, but on objects above the surface. On the other hand, these objects are not completely modeled. In Maas (1996), the probability of the interest operator detecting identical points in all involved images was estimated to be 0.65^{n-1} , with n being the number of images in which a point is required to be detected. In combination with the average visibility of points in 12.25 images (derived from the average overlap), this efficiency of the interest operator of 65 percent leads to a significant loss of points. Due to the characteristics of the interest operator and this loss of points, buildings are often modeled rather incompletely. In some cases, only one or two points of a roof were matched, and terrain points at the foot of buildings are often missing.

Dataset Talegnas

Applying the same procedure to the Talegnas dataset, again an average of 7000 points per image was detected by the interest operator. A total of 2279 3D points could be reconstructed from these data, when each point was required to be matched in at least five images. The best point was matched in 14 images. The reason for the poorer yield as compared to the Urmein dataset was — in addition to the smaller image

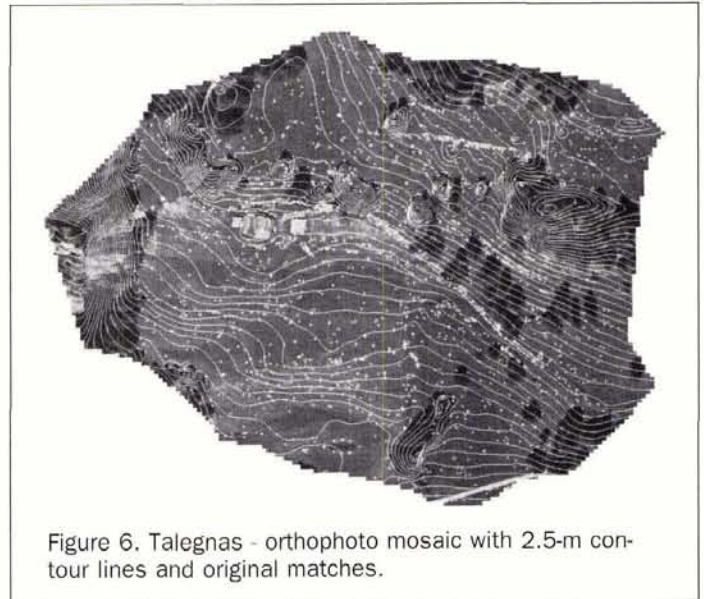


Figure 6. Talegnas - orthophoto mosaic with 2.5-m contour lines and original matches.

overlap of 65 percent instead of 70 percent — mainly the reduced efficiency of the interest operator, which was estimated to be 55 to 60 percent in this dataset. The average standard deviations in the X, Y, and Z coordinates were 0.023, 0.023, and 0.095 m, respectively (0.03 percent of the flying height above ground). An orthophoto with a 2.5-m contour line overlay mosaic based on the DSM data is shown in Figure 6. Again, no post processing, filtering, or blunder removal has been applied to the raw DSM data. A visual analysis of the result shows no gross errors in the reconstructed 3D points. Problems occur mainly with trees which are not detected by the interest operator or not completely modeled; also, the two buildings in the images are not well represented.

Conclusion

Digital aerial photogrammetry is still dominated by scanned imagery and will remain so for quite some time. Nevertheless, the use of solid-state sensor cameras in aircraft may already today be interesting for a number of large-scale applications.

The results achieved in the two pilot studies on the heli-

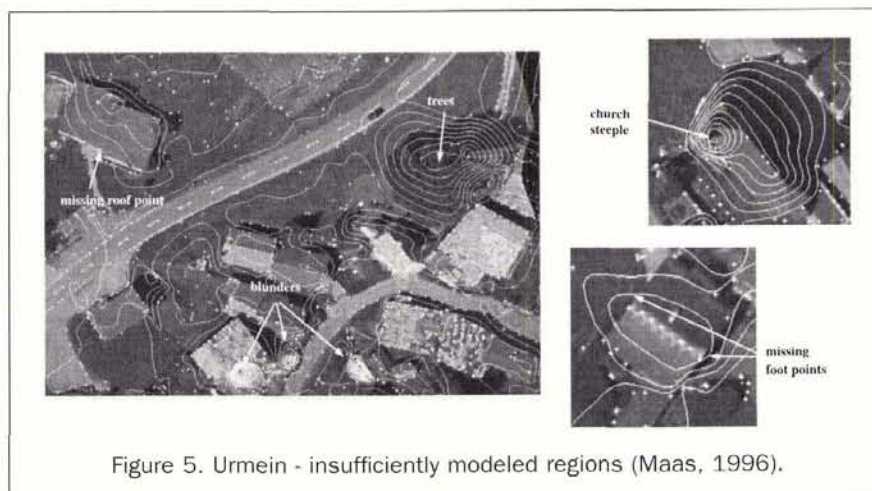


Figure 5. Urmein - insufficiently modeled regions (Maas, 1996).

copter-based use of a high-resolution still-video camera for aerotriangulation and digital surface model determination are quite promising. Over areas of 400 by 300 m and 520 by 500 m, externally verified accuracies of 2 cm for planimetry coordinates and 5 to 6 cm for height coordinates could be achieved in a semi-automatic digital aerotriangulation, and, as a consequence of gross multi-coverage, a precision of 10 cm (0.03 percent of the flying height above ground) could be achieved in automatically determined digital surface models. With the newest generation of still-video cameras with doubled resolution, accordingly better results can be expected. The practical use of such cameras offers the advantages of a direct data flow, with the potential for on-line processing and better radiometric characteristics, and it can be considered an economic solution. Disadvantages are the still limited resolution and the necessity of rather large targets when signalized points are to be used.

It is obvious that the use of a still-video camera in a helicopter can only be considered a compromise. Handling problems, limited control and storage capacity, and the unstable camera body are opposed to a professional use. Nevertheless, the results achieved in these studies can be considered representative for the use of CCD cameras in large-scale aerial applications, and rigid-body large-format CCD cameras, which can be permanently installed in an aircraft and interfaced to an on-board host computer, are already on the market. As the costs of such components are dropping, digital aerial imaging systems will probably soon be available for a number of applications.

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