'Photogrammetric Week '97' D. Fritsch & D. Hobbie, Eds., Wichmann Verlag, Heidelberg, 1997.

Design Concepts for Digital Photogrammetric Cameras

ALEXANDER HINZ, Oberkochen

ABSTRACT

Digital camera systems will gain increasing ground in various fields of application. The exacting requirements made by photogrammetry on resolution and accuracy are pushing current sensor technology to or beyond the limits of what is technically feasible today. The present paper describes and analyzes solutions based on CCD line and various area sensor configurations. Prospects and risks of digital cameras are discussed.

1. INTRODUCTION

Airborne remote sensing will continue to be indispensable in the future for the generation of images with a high ground resolution of clearly below 1 m. Suitable sensors are currently the missing link required to close the digital chain from image recording to plotting.

The decisive advantage of a digital sensor system is the fast availability of data after or even during the mission. In military reconnaissance, this is of paramount tactical importance. In civilian applications, it is a valuable benefit, in particular for disaster missions in the event of floods, storm damage, large fires, volcano eruptions etc. During the days immediately after the earthquake in Kobe / Japan in January 1997, for example, more than 10 aerial survey companies took more than 20000 aerial photos over an area of 5000 km² to establish the damage incurred (Hasegawa, 1997).

Further examples are found in industrial applications such as the monitoring of roads, railways, electrical supply lines etc. In these areas, it may not always be necessary to store all image data, because it is often only the changes from an earlier situation which are of interest here. High resolutions open up new fields of application such as the determination of building-site excavations, waste dump fills, material removal and earthfills in road construction. Changes can be determined here by the comparison - automated if possible - of the current aerial photo with existing image material.

Apart from the performance of classical photogrammetric tasks, the spectral sensitivity of the CCD chips which reaches into the near infrared opens up new fields of application such as the determination of vegetation damage or the assessment and classification of agricultural land. Further topics in this context are the protection of coastal areas, sewage discharge and silting.

The high sensitivity of a CCD sensor, along with its wide dynamic range, offers distinct radiometric advantages over film material, as it permits markedly higher contrast to be recorded in the image. In urban areas, in particular, this even enables the recording of heavily obscured structures. Whereas a film generally does not provide a dynamic range of more than 6 bits, a CCD chip offers 10 to 12 bits.

The following basic digital sensor designs are conceivable for the future:

- line sensors
- TDI-line sensors
- large-area array sensors
- multi-area array sensors

2. REQUIREMENTS

The standard against which digital cameras are measured is the existing film-based camera systems featuring minimum exposure intervals of up to 2 seconds.

If the minimum ground resolution is specified at 0.1 m, and assuming a typical aircraft velocity of approx. 50 m/s, this results in a maximum exposure time of 2 msec (1/500 s) for the CCD. When longer exposure times are used, a degradation of the ground resolution must be accepted due to image blur in flight direction. Depending on the type involved, the sensitivity of CCD chips ranges between 100 and 1000 ASA, which means that image motion compensation is also required in a digital camera, especially in poor light conditions.

To achieve the specified ground resolution at a flying altitude of 1000 m, the optical axis has to be kept stable within 20 arc sec during the exposure. With an exposure time of 10 msec and the camera installed in a fixed position, the angular motion of the aircraft must not exceed 0.5 degrees/s. This is a rather stringent requirement, considering that motions of about 1 degree/s [Light] are very likely to occur in typical flight conditions. Therefore, we are again confronted with the need for the same stabilization of the optical axis as that implemented for high-resolution photos in aerial survey camera systems in the form of gyro-stabilized suspension mounts.

3. LINE SENSORS

3.1 Line Features

Various manufacturers offer suitable high-resolution CCD modules as linear lines. Currently 12K line sensor chips are in production, in future 24K chips might be available at affordable prices < 10T$. This devices permit the complete recording of a scene in one dimension and at a high resolution. During the photoflight, the second dimension is recorded as a result of the aircraft motion (push-broom principle). A fixed relative orientation of the individual photo strips, however, does not exist, due to the aircraft motion. To be able to correct this when joining the individual strips together during postprocessing, a high-precision positioning system must be connected to the digital camera. Suitable configurations are provided by coupled GPS and inertial navigation systems (INS). These systems must offer not only high accuracy but also a fast measuring rate for the assignment of the taking angle and spatial position to each exposed line image.

The push-broom principle always leads to different geometric measuring accuracies along and across the flight direction, resulting in image blurs in the flight direction caused by the finite exposure time. However, the compensation of this forward motion in the form implemented in state-of-the-art aerial survey cameras with FMC (Forward Motion Compensation) is not possible here.

This problem can be solved by the use of multi-line arrays featuring Time Delayed Integration (TDI) of the pixel rows for the electronic compensation of the scene motion on the chip. For this purpose, the pixel clock rate needs to be adapted to the image rate (Holst, 1996).

The extension of a line camera for several color channels is relatively simple. Several lines which permit color recording and multispectral recording at several different wavelengths can be arranged in the image field of the camera lens.

The systems described until now, i.e. those which can be used for documentation and interpretation purposes where no geometric measuring accuracies are required, are usually based on single lines with a CCD line width of one pixel. The VOS 60 System (Claus, 1995) should be mentioned here as an example of a system suitable for reconnaissance applications where no stereo capabilities are needed.

The three-line principle (Hofmann et al., 1993) permits stereo images to be taken by simultaneous recording of forward, backward and nadir channels. In conjunction with GPS-INS and special plotting techniques, it also enables the geometric measurement of the recorded images. This configuration is used by **MOMS** and **DPA** in remote sensing and photogrammetry, and by **HRSC** and **WAOSS** (Neukum et al., 1995; Sandau & Eckhardt, 1996) for the exploration of Mars. For several years now, MOMS and DPA have been the subject of tests aimed at a variety of objectives (Hofmann et al., 1993) and will be discussed in another paper presented at this conference (Fritsch, 1997).

3.2 Testing of the HRSC Sensor of DLR with RMK-TOP

To test the potential of the 3-line principle in combination with an aerial survey camera, the German Aerospace Agency DLR and the companies Rheinbraun and Carl Zeiss agreed to conduct a joint test series. Carl Zeiss made available an RMK-TOP 15 system for this purpose. The test program and the evaluation were performed by M. Brand, E. Ress and G. Neukum of the DLR Institute for Planetary Exploration and by J. Albertz of the Institute for Photogrammetry and Cartography at the Technical University of Berlin. The missions were flown by Rheinbraun.

On the basis of the High Resolution Stereo Camera (HRSC) developed for the “Mars 96” space mission, a modified camera version for combined use with an RMK TOP aerial survey camera was manufactured by the Institute for Planetary Exploration and subjected to trials on February ´97 in the Mönchengladbach area.

The HRSC camera with a total of 9 lines (5k pixels/line) was mounted on an RMK-TOP 15 camera instead of the T-MC film magazine. The stereo base of the three-line geometry for black-and-white photography was ±21.5° in this case. Six further channels were available at ±18°; ±14.5°; ±4° for the optional recording of further colors and spectral channels. No modifications were required on the camera system; only the shutter and diaphragm were set to full aperture. The HRSC was controlled via a PC. The image data was recorded by a “DIR-1000” high-speed tape recorder provided by Sony.

The position of the HRSC during the mission was determined by differential GPS and the camera attitude was corrected by the T-AS active stabilization platform. Navigation was performed via the T-Flight photoflight management system and the T-NT navigation telescope, the latter being also used for setting the yaw angle on T-AS. A second RMK was operated simultaneously with the HRSC to make exposures on film.

Weather conditions during the tests were poor, with gusts of wind and low cloud cover. "Normal" photoflights would not have been flown on such days. Photography on film had to be stopped at times due to inadequate light conditions, whereas the HRSC continued to operate without any problems. The cloud cover forced the pilot to fly at low altitudes of 500 m to 1500 m above the ground. This resulted in rectangular ground pixels of approx. 2 cm x 14 cm and 7 cm x 14 cm.

The image data is being processed at the Institute for Planetary Exploration using the stereo software written for the “Mars 96” mission and appropriately modified for aircraft data. The sets of image data recorded above different types of terrain prove the successful performance of the trial flights.

A major benefit of the HRSC lies in the easy adaptability of the sensor system to the RMK-TOP 15 (or 30) system frequently used for photoflights. No modifications are required on the existing RMK configuration. Even the use of the system in small aircraft presents no problems. For multi-spectral applications, the nine CCD channels can be equipped with different spectral filters.

Following the completion of this trial, a second HRSC system with its own 175 mm optics and an additional gyro system was successfully tested in the Etna area in May ´97.

4. LARGE-AREA ARRAY SENSORS

This is the most obvious option for the replacement of large-format film. It permits the generation of CCD pixels less than 10 µm in size, corresponding to the resolution of photographic film material. Due to the advances made in the production technology of large silicon wafers, chips with a pixel number in excess of 5K*5K would now seem to have come into reach. The low yield of chips with tolerable pixel errors, however, pushes up prices to more than $ 50000 per unit. Other fields where such large-area arrays might be used on a large scale are not yet in sight, and a dramatic drop in prices as currently experienced in CCDs for the mass market for camcorders or simple digital cameras (<1K*1K) can therefore not be expected.

'Photogrammetric Week '97' D. Fritsch & D. Hobbie, Eds., Wichmann Verlag, Heidelberg, 1997.

Restrictions in application are currently set by the readout speed of the chip architectures available. Without multiple tapping, the readout rates are several seconds per image. Dalsa successfully demonstrated a maximum rate of 2 images per second (60 MHz clock rate of the chip) by quadruple tapping of a 5K*5K detector. The cost of this solution, however, is extremely high, ranging in the order of more than $100000 at present.

Image motion compensation can be achieved either by a purely electronic method (TDI) as described in 3.1 or by opto-mechanical means.

The virtually complete utilization of the chip surface by sensitive CCD pixels (full-frame architecture) necessitates an additional shutter device for exposure time control. To avoid any geometry distortions, a central shutter such as that used in classical aerial survey cameras is required. For this purpose, the same technical solutions as those implemented in film-based aerial survey cameras can be used here. To ensure precise exposure stations during the photoflight, the shutters must feature short access times - a requirement which has already been met today by the pulsed shutter of the RMK TOP.

Ranging up to 1000 ASA, the sensitivity of monochrome-sensitive chips is relatively high compared with conventional film material. When using a fast lens in good light conditions, it may be possible to dispense with image motion compensation, if a certain loss in quality is acceptable.

In color sensors, on the other hand, sensitivity is reduced by the application of color filters in front of the CCD surface elements. Either the light collected by the lens is distributed to CCD chips in different optical channels, each preceded by a color filter (multi-chip camera), or a matrix of different color pixels is applied to the surface of a CCD chip. Both designs lead to significant losses in light in practical use, with the resultant increase in exposure time diminishing the advantage over film.

5. MULTI-AREA ARRAYS SENSORS

Budget-priced CCD chips will be available in the future from the video and camera market. The area sizes for these applications, however, are limited to a few cm² and will barely exceed 1k*1k to 2k*3k. In the high end market of professional photography digital cameras with 4K*4K chips start to get available. However this is far away from the demands of high-resolution systems needed in aerial photography. Therefore several of such "stamps" need to be linked together to fill the image plane. This can be achieved by arranging them in the large image field of a lens in such a way that as many elements as possible are lined up without gaps. These butting techniques are extremely complex from the technological viewpoint, and a small gap will eventually always remain in the image field. The number of individual CCD chips to be butted cannot be chosen arbitrarily. Depending on the chip architecture, only 1 or 3 lateral surfaces are available to which further elements can be fitted without the occurrence of large gaps.

A different approach is the use of so-called optical butting techniques, which are familiar from satellite-based sensor systems such as Earlybird (Earthwatch), where optical devices such as prisms and beam splitters divide the image field into separate segments which are then imaged on the individual CCD areas.

The advantage of this technique is the possibility of parallel data recording and data processing in several different channels. It also permits the use of components from other market sectors (e.g. video technology, consumer goods) which are produced in large quantities at an economy price and are available off the shelf.

The challenges to be met here are the high geometric orientation stability of the chips in relation to each other and the neccesary high precision of installation in the image plane.

The compensation of image motion can be implemented in the same way as in the large-area array sensor described in 4.

Alternatively, a lens could be assigned to each individual CCD chip and the optical axes aligned in such a way that a large image field is covered on the ground. The complete configuration would then

'Photogrammetric Week '97' D. Fritsch & D. Hobbie, Eds., Wichmann Verlag, Heidelberg, 1997.

be combined as a lens matrix in a stable structure. Once again, the result is a modular design which permits parallel readout, preprocessing and storage. Due to the small image fields involved, less stringent requirements have to be met by the individual lenses than by a large-format camera. A further decisive benefit is the scalability of this design with respect to image field and resolution. The overall system including the optics comprises a large number of identical modules permitting the use of economy-priced production technology.

A similar design has been implemented in the Carl Zeiss reconnaissance cameras KS-153 Pentalens and Trilens for the across-flight direction in order to ensure maximum image field coverage.

6. DATA STORAGE

A common feature of all configurations discussed above is the production of large data volumes. A conventional photogrammetric photo stores a volume totalling about 8 Gbits (b/w) on film by an analog technique. This data quantity is produced at a repetition rate of up to 2 seconds, resulting in data rates of >> 1 GBit/s. Data volumes of this size can not yet be handled by current storage and readout technology.

In a typical photoflight, 500 - 1000 exposures are made (this corresponds to 1 or 2 film rolls). This means that a total memory capacity of 1 Terabyte is required for the raw mission data which has to be handled on board the aircraft.

Even a digital camera with a resolution of 10K*10K in the image field and a dynamic range of 8 bits still provides 800 Mbits of raw data per image. A reduction can be achieved by image data compression immediately after photography.

Existing configurations use recording systems based on digital tape recorders, permitting data rates of 512 Mbit/s with a total capacity of 800 Gbits per tape. The tapes can be rapidly and easily exchanged, and no restrictions must be imposed in view of the aircraft's load capacity.

The mass storage media available must be checked for their suitability for air-borne use. Budget-priced options such as hard disk arrays known from database systems must be subjected to critical assessment. Resistance to low air pressure, vibration and temperature variations, in particular, is a decisive criterion determining usability in photoflights.

The digital tape recorders currently available and suitable for airborne use are special-purpose equipment manufactured in small quantities. This accounts for the high prices of some of these data storage systems, ranging well above US $ 250000.

7. OUTLOOK

Digital cameras and film-based systems will complement one another in the future. Technical configurations of a digital system have been presented and demonstated on various occasions.

Table 1 gives an overview of the major benefits and drawbacks of line array and area array sensors for photogrammetric cameras, from the viewpoint of state-of-the-art technology.

A major obstacle with respect to market acceptance must be seen in the investment costs required by high-resolution CCD chips and data storage, which still are extremely high. The standard against which digital cameras are measured is the existing film-based systems. In the final analysis, it is the total cost of a digital image compared with that of a photo digitized in a scanner which will be the decisive factor.

Once the necessary key components are available at an affordable price, fully digital systems will be more widely used. The next 10 years will most certainly be highly interesting in the camera business.

'Photogrammetric Week '97' D. Fritsch & D. Hobbie, Eds., Wichmann Verlag, Heidelberg, 1997.

	Line Sensor	**Area Sensor**
Availability	single line chips from office communication systems multi-lines in small quantities from use in niche applications	Large-area arrays only for special niche applications up to 2K*3K from digital cameras for professional photography
Cost	single lines > 1T\$ TDI chip > 4T\$	Large-area (4K*4K) > 40 T\$ Medium format (2K*3K) > 20T\$
Image motion compensation	Not possible for single lines possible for multi-lines (TDI)	Electronic (TDI) and opto-mechanical techniques available
Stabilization requirements	single pixel accuracy, registration of GPS and INS data, multiple pixel accuracy with TDI	Stable during exposure time of single frame
Geometric measuring accuracy	Defined by line across the flight direction, dependent on GPS-INS, v/h-value, exposure time along the flight direction	High due to fixed, defined geometry of CCD pixels
Postprocessing required	Extensive due to postprocessing of INS-GPS data to sort the lines	Little, lining up of single frames for strip image
Color capability	By simple addition of further line elements	multi-chip solution or color mosaic matrix (reduced resolution)

Table 1: Comparison of line and area arrays.

8. REFERENCES

Claus, M. (1995): Demands on Electro-Optical Cameras for Sensing and Mapping photogr. week ´95 Wichmann, Karlsruhe, pp. 37-44.

Fritsch, D. (1997): Experiences with the airborne three-line camera system DPA photogr. week ´97 Wichmann, Karlsruhe.

Hasegawa, H. (1997): Mapping the Biggest Earthquake in Recent Times GIM vol. 11 no. 5, pp. 30-33.

Hofmann, O., Kaltenecker A., Müller F. (1993): Das flugzeuggestützte, digitale Dreizeilenaufnahme- und Auswertesystem DPA. Photogr. week ´93 Wichmann, Karlsruhe, pp. 97-108.

Holst, G.C. (1996): CCD-Arrays, Cameras and Displays, SPIE Bellingham 131p.

Light, D. (1996): Film Cameras or Digital Sensors? The challenge ahead for aerial imaging. PE&RS Vol. 62, no., pp. 285-291.

Neukum, G., Oberst, J., Schwarz, G., Flohrer, J., Sebastian, I., Jaumann, R., Hoffmann, H., Carsenty, U., Eichentopf, K., Pischel, R. (1995): The multiple Line Scanner Camera Experiment for the Russian Mars 96 Mission, photogr. week ´95 Wichmann, Karlsruhe, pp. 45-62.

Sandau, R., Eckardt, A. (1996): The Stereo Camera Family WAOSS / WAAC for Spaceborne / Airborne Applications, International Archives of Photogrammetry and Remote Sensing, Vol XXXI, B1, Vienna, pp. 170-175.