Photogrammetric Record, 14(84): 943–956 (October 1994)

DIGITAL PHOTOGRAMMETRY AT THE *INSTITUT CARTOGRÀFIC DE CATALUNYA*

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(Paper read at a Technical Meeting of the Society on 14th March, 1994)

Abstract

Since its foundation in 1982, the Institut Cartogràfic de Catalunya has been dealing with digital images. Though digital images and techniques were initially confined to remote sensing, they have been gradually transferred to and combined with photogrammetry. In addition to the development of remote sensing and digital orthophotography systems, this expertise has facilitated the introduction of commercially available digital photogrammetric systems (scanning and stereocompilation) which are now in full operation. The paper describes the experience in scanning, orthophotography production and stereocompilation, draws some conclusions and gives an insight of the future of digital photogrammetry.

INTRODUCTION

THE Institut Cartogràfic de Catalunya (ICC) is the mapping agency of the autonomous region of Catalonia. Although production oriented, the ICC has a research and development infrastructure. By interleaving production and development and by shortening practical world feedback, we are able to react quickly to technological innovation. Digital photogrammetry is an example of a new technology being introduced smoothly by taking advantage of a background in remote sensing and photogrammetry and of an existing technical infrastructure.

The path to digital photogrammetry was paved a long time ago when, in 1977, one of the authors started the development of remote sensing software for processing Landsat images at the Technical University of Catalunya (Colomer, 1979). At that time, the primary goal was thematic feature extraction for land use analysis. Even though no geometric correction software for georeferencing was developed in the first versions, the project had the benefit of making us acquainted with digital images and digital image processing. In 1980, the georeferencing modules were added. In 1981, the team working at the university moved to the ICC and, in 1985, the first map series from satellite imagery was produced. It was based on false colour satellite ortho-images at 1:100 000 scale from Landsat 5. Therefore, when we started to address the digital orthophotography issue, both production and development teams were ready to deal with digital images. First experiments with digital orthophotography were made in 1986 and the first operational system was put into production in 1988. Over the years, we have developed a general concept for point determination and general sensor orientation (Colomina *et al.*, 1992) and we have started to apply photogrammetric methods to an increasing variety of digital sensors, including SPOT (Palà and Pons, 1994), ERS-1 radar georeferencing (Palà and Corbera, 1993), interferometry for DTM generation (Castillo and Arbiol, 1994) and now the CASI airborne multispectral scanner.

The paper is organized as follows: firstly, scanning and image compression are discussed; after that, our current system for orthophotograph production is reviewed; then we illustrate our experiences with digital stereoworkstations in stereoplotting projects; finally, we introduce our general concept for photogrammetry and remote sensing.

SCANNING

Scanning is the process in a digital photogrammetric workflow in which an analogue photographic film is converted into computer readable format. Modern high performance cameras with forward motion compensation (FMC) and high resolution films offer considerable potential for detail detection and recognition which is easily exploited on analytical systems with appropriate optics. Therefore scanning should be able to preserve the information content of such modern camera/film combinations. In our opinion, this is the current challenge for photogrammetric scanners. During the Joint ISPRS/OEEPE Workshop on analysis of photo-scanners, the following requirements were specified (Kölbl and Bach, 1994):

geometric accuracy:	$\pm 2\ \mu m$
pixel size:	$10\ \mu m$ for black and white and $15\ \mu m$ to $20\ \mu m$ for colour
density ranges:	0·1 D to 2·0 D for black and white and 0·2 D to 3·5 D for colour
noise:	0·03 D to 0·05 D for $10\ \mu m$ pixel

good colour reproduction
data compression
comfort of document handling

To these requirements, we should add the absolute absence of visible artefacts in the scanned image. Note that any artefact, perhaps virtually invisible shortly after scanning, can become clearly visible during enlargement and image enhancement processing. A reasonably complete list of possible quality problems can be found in Baltsavias (1993). If high quality scans can be achieved, then the user may see scanning as a method to freeze film distortions due to improper manipulations or storage. Non-photogrammetric applications, such as the production of contact copies or enlargements from a database of digital images, can be envisaged as soon as the technological advances improve the output resolution of cheap plain paper printers and plotters.

Scanning for Digital Orthophotographs: the Past Experience

We started scanning aerial photographs with an in house development for the Gestalt Photomapper which involved adding an analogue to digital converter to the output of the CRT analogue scanning device. Our enhanced Gestalt turned out to be a flatbed, patch oriented black and white scanner that delivered 22·7 μm 8 bit pixels. We used this system in our digital orthophotograph production workflow from 1988 to the end of 1989 with problems in image quality due to the radiometric differences between adjacent image patches. Since the system could not deliver overlapping patches, the radiometric matching techniques were not able to solve the chessboard effect completely.

When the Gestalt was taken out of operation, we switched to a Joyce-Loebl Scandig 2605 flying spot drum scanner, which is widely used in the publishing industry. The nominal radiometric range is 0·2 D to 2·0 D for black and white with pixel sizes ranging from 12·5 μm to 1000 μm and with 8 bits per pixel. The Joyce-Loebl scanner does not offer any way to control the radiometry of the scan; that is, there is no possibility of modifying the radiometric transfer function for matching the radiometry of the film. In practice, this means that if the film densities span outside the system's density range, the resulting image will show saturations, as happens with photographs with very clear and dark areas showing peaks at both ends of the histogram (bimodal images). The concept of matching (or tuning) the scan to the film consists in using the available density range of the scanner to capture the most relevant densities of the film.

Because of this lack of radiometric matching capabilities, we use the Joyce-Loebl scanner for contrast compensated (dodged) black and white and colour positives.

Newton's rings may appear when scanning thin films if they are not well fixed to the drum. Regarding geometric accuracy, we measured r.m.s. errors of 13 μm along the drum circumference axis and 9 μm on the rotation axis direction when scanning 25 μm pixels. We also found that the lack of an online image display was an operational drawback because radiometric problems could not be detected until the image was examined on the processing workstations after a time consuming data transfer. Typical scanning times for 25 μm images are 35 minutes for black and white and 90 minutes for colour; data transfer over Ethernet takes an additional 30 minutes for black and white and 90 minutes for colour. Despite these limitations in speed and accuracy, the Joyce-Loebl scanner has supported all our digital orthophotography workload since 1989.

The Current Environment: the PS1 Scanner

The PS1 from Zeiss/Intergraph (Faust, 1989) is a flatbed black and white and colour scanner based on a linear array of 2048 CCD elements designed to operate in the 0·2 D to 2·0 D range with pixel sizes of 7·5 μm, 15 μm, 22·5 μm, 30 μm, 60 μm and 120 μm and with 8 bits per pixel. The photograph is scanned by swaths as the film, mounted on a high precision stage, moves under the scanning head assembly. The PS1 outputs pixels proportional to either transmissivity or density values from positive or negative photographs and optionally compresses the image "on the fly" using a hardware board that implements the JPEG (Joint Photographic Experts Group: a group of experts from the ISO and the CCITT) compression standard. Colour films are scanned in three separate runs with the corresponding red, green and blue (RGB) filters. Measured geometric accuracy using a calibration grid on a glass plate is 1·4 μm.

In contrast to the Joyce-Loebl scanner, the PS1 provides radiometric control by computing a transfer function that converts the internal 13 bits input to the 8 bits per pixel output, based on the previously measured maximum and minimum density values of the film. The function is linear in the case of selecting transmissivity as the scanning mode and logarithmic in the case of scanning in density mode. The user can interactively modify the transfer curve (called the gamma curve in PS1 terminology) when dealing with radiometrically extreme or complex photographs (with bimodal histograms) for which the default transfer function gives saturated images. In this case, the radiometric control allows the use of trial and error for obtaining a compromise image. During this iterative process, the user can take advantage of the histogram analysis tools available and of the instantaneous display of the results of changing the scan curve.

Because of the availability of the radiometric control and since the PS1 can deliver a positive image from a negative, one may try to spare photolaboratory processing and scan negative films with rather larger density ranges. Our first results were really discouraging because of the presence of noise and radiometric artefacts (a vertical line) at the beginning of each swath on dark homogeneous areas; that is, areas with a low level signal for which the non-linear density mode curve was amplifying more than the high level signal of the clear areas. In practice, the scanner could only deliver eight tones when scanning a calibrated grey level bar of 14 steps ranging from 0·2 D to 2·04 D. Using the same bar, the Joyce-Loebl scanner was able to capture 12 grey levels without artefacts.

Later on, during a maintenance service, the hardware engineers discovered that the scanner was operating far off its nominal values because of an outdated component in the illumination and refrigeration path. A quick replacement immediately solved the thermal noise and strip problems. The number of grey levels captured jumped immediately to 12, thus allowing a wider effective range to operate with and consequently to scan black and white negative films directly without dodging. For colour negatives, the situation is quite difficult because of the effect of the colour filters used during imaging, these effects being compensated during the photolaboratory process for obtaining positives. The current remaining artefact is a faint radiometric drop from the centre of the swath to its borders that can not be corrected completely during the internal normalization procedure aimed at compensating the inhomogeneities of the individual elements of the CCD array. Fortunately, this remaining artefact is invisible except, again, on large dark homogeneous areas (such as the sea). Changes in the CCD normalization subsystem have already been announced in order to remove this residual problem.

Although the concept of tuning the scan to the film can certainly be used for each photograph, we do not use this methodology for orthophotography projects involving mosaics. The reason is that individually optimized scans easily produce radiometrically different images from the neighbouring photographs used for mosaicking. As will be mentioned later, we prefer to enhance the orthophotograph once the mosaic is complete rather than to enhance the individual photographs beforehand. Therefore we perform an initial analysis of the photographs involved in a project (a photogrammetric block) to select representative samples which are then scanned at low resolution (120 μm) for interactive tuning. Then the default density settings for the whole block are determined by taking the lower and higher minimum and maximum density of the samples. With no difficult photographs requiring the trial and error radiometric tuning, the PS1 throughput is a full black and white compressed image in less than 10 minutes at 15 μm pixel size. Downloading the image to a 2·3 Gb Exabyte tape takes an additional 6 minutes. Scanning and data storage timings are roughly three times more for colour scans.

In summary, scanning is a very delicate process requiring the full attention of trained operators in order to obtain good quality digital images. In this aspect, the requirements are probably similar to those of the professional publishing industry. From our experience, we would emphasize the fact that scanner vendors must provide clear and well documented diagnostic tools for helping the user to monitor malfunctions or departures from the geometric and radiometric nominal characteristics of the system and that a scanner should always be treated as a precision instrument.

Image Compression

Image compression is essentially a tool for alleviating data management, including archiving and transfer between workstations. In our system, with an average compression ratio of 4, the typical size for a 15 μm image data set is reduced from 250 Mb to 63 Mb, with an equivalent reduction in data transfer time and storage space. It also speeds up disk input/output because more pixels are transferred per disk operation. However, compression doesn't reduce the size of the image in main memory or, therefore, the number of pixels to be processed (Table I).

TABLE I. Image compression.

			Orthorectification	
	PS1 scan (minutes)	*Exabyte store (minutes)*	*CPU (minutes)*	*Elapsed (minutes)*
Colour 15 μm non-compressed	3 × 17	3 × 21	5·5	9·5
Colour 15 μm compressed	3 × 10	3 × 6	5·5	7·7

Three separate bands on input and output in the non-compressed case. Three separate compressed bands on input and one RGB compressed band on output in the compressed case. Recitification of 12000 × 12000 pixels on an Intermap 6487 with the VITEC image processor.

The JPEG compression/decompression standard implemented in the PS1 uses a quality parameter called the Q factor for controlling the degree of compression to be applied to the image. It is up to the user to set a value for this parameter, which affects the amount of information lost and thus the final size of the image file and the compression ratio achieved. This ratio is different for each image and for the same image scanned again with different radiometric parameters or resolutions because the JPEG compression ratio is data dependent. Images with fine details achieve a lower compression ratio than others with many homogeneous areas. Colour compression achieves higher compression compared to compressing each band individually because the JPEG method performs an initial colour transformation (RGB to luminance and chrominance) before applying the compression algorithm. Since the PS1 scans colour in three separate passes, it is not able to perform a colour compression directly; instead, each colour band is compressed separately.

Although image compression certainly helps in managing data, the user is confronted with a potentially dangerous situation because the Q factor does not give any quantitative measure of the information lost during compression; therefore, the user has to work subjectively. A second concern comes from the fact that a workflow that applies image enhancements in separate job steps (reading and writing at each step) is concatenating the compression effects and perhaps reducing the benefits of the enhancement algorithms. Although an over aggressive compression produces blocking artefacts which can be easily seen in homogeneous areas and can be used as an indication of an excessive compression, lower Q factor effects are not seen at all. Heipke (1993) has reported random distortions of less than 0·5 pixels using least squares matching methods for comparing compressed and uncompressed satellite and computer vision test images. In our case, after visually testing the compression effects on fine detail, we decided to use a Q factor of 30 (from a scale ranging from 1 to 799) in our digital photogrammetric workflow for stereoplotting. Loss of pointing accuracy because of compression has not been tested yet. Table II shows our typical compression ratios for $Q = 30$.

TABLE II. Usual compression factors achieved with $Q = 30$.

	7·5 µm	*15 µm*	*30 µm*
Colour positive (individual compression)			R = 4·0, G = 4·6, B = 4·8
Colour positive (joint colour compression)			RGB = 8·9
Negative	5·1	4·0	3·8
Positive	5·3	4·3	4·2

DIGITAL ORTHOPHOTOGRAPHY

In 1982, shortly after the foundation of the ICC, the near total lack of topographic maps at 1:5000 scale and a limited coverage at 1:25 000 scale was the context in which the decision to put a Gestalt Photomapper IV into production was made. Very fast orthophotograph and elevation data generation were the goals of the project. Over time, the project had the additional benefit of triggering research and development activities in the field of digital photogrammetry and terrain modelling. In 1984, the Gestalt hardware and software were modified to allow for a digital output of the orthophotography and of the digitized aerial images. In 1986, the photogrammetric and numerical aspects of orthophotograph generation were investigated for metric accuracy, radiometric resolution and computability (anchor point approach) (Arbiol *et al.*, 1987a). By 1987, a digital orthophotography system concept was already available (Arbiol *et al.*, 1987b).

The first operational system was implemented in 1988. It was able to produce up to 15 black and white non-mosaicked orthophotographs per day on a MicroVax 3600. The final map finishing tasks were done in the photolaboratory using traditional manual procedures. At that time, the old but accurate Gestalt was used as a flat bed scanner. In 1990, the system was enhanced with interactive mosaicking capabilities and completed with a large format raster plotter and CAD workstations for performing the finishing of the orthophotomap (geographical names placement and automatic generation of map grids, frames, legends and marginalia), therefore replacing the manual photolaboratory tasks.

These activities were complemented by the development of a countrywide raster elevation database (15 m grid) and a bundle aerial triangulation system. Sustained production throughput, with two workstations for image rectification and two CAD workstations for map finishing, was one orthophotomap on film ready for printing each two hours. A complete description of the system, as it was in mid-1991, was given by Colomina *et al.* (1991). In 1992 the 1:5000 scale orthophotomap of Catalonia was finished together with the elevation database. After producing the 1:25 000 black and white orthophotomap during the 1992–1993 period, the colour orthophotomap project at 1:25 000 scale from a 1:60 000 scale photography began in late 1993.

Challenges and Developments

Over the years we have realized that our image rectification software has remained almost unchanged while the image processing part has undergone continuous development for implementing new capabilities as new requirements have been set. The colour orthophotomap project has stretched our system to its practical operational limits, not just because colour means three times larger data set sizes to deal with, but also because the requirements of a true seamless mosaic, a smaller pixel size for on screen map updating and a high image quality has forced us to develop and implement increasingly sophisticated and computer intensive image processing algorithms for image enhancements.

Table III shows timings for colour orthophotograph production. They correspond to the rectification, mosaicking and enhancement of two partially overlapping 150 Mb images at 1:60 000 scale, scanned at 25 μm (1·5 m) where the final orthophotograph has a 1·8 m pixel size. As can be seen, file access (input/output) is the main bottleneck in our current system. With our present configuration (two workstations), a mosaicked colour orthophotograph can be produced each 4 hours (in fact we are able to produce one each 2·6 hours by running the two final job steps in batch during the night). For comparison purposes, we include the rectification timing on a Vitec-based 6487 digital photogrammetric stereoworkstation from Intergraph.

TABLE III. CPU and elapsed times for individual job steps.

	VaxStation 4000/90		*Vitec-50*	
Step	*CPU (minutes)*	*Elapsed (minutes)*	*CPU (minutes)*	*Elapsed (minutes)*
Preparatory tasks (file reformatting)	16	38		
Image rectification (two images)	40	62	11	19
Preparation for mosaic	3	22		
Drawing of the mosaic seam (manual)		20		
1st mosaic pass (colour matching: 3 steps)	52	150		
Refinement of the seam (manual)		20		
2nd mosaic pass (merge: 1 step)	10	34		
Image enhancement filters (2 steps)	95	153		

Anchor points each 10 pixels. Cubic convolution sampling. Non-compressed input and output files on one single disk drive.

It is interesting to note that image processing (colour matching and enhancement filters) accounts for 68 per cent of the CPU time. Although a detailed description of the image processing processes is outside the scope of this paper, it is worth noting that the image enhancement filters involve a CPU-intensive 7 × 7 convolution and a local colour enhancement of the 150 Mb mosaicked orthophotograph. The convolution filter is aimed at restoring the image from blurring due to diffraction, imaging system aberrations, atmospheric turbulence, motion and scanning. A detailed paper on these techniques by Prades *et al.* (1994) has been submitted to the ISPRS Commission III Symposium in Munich (September 1994).

It may be argued that some of the image processing refinements and the improved pixel size are not worth the computer time devoted to them. For example, it is known that bilinear pixel interpolation during rectification normally gives a good enough quality image and that pixel sizes for halftoning do not need to be less than 0·1 mm for achieving good printing quality (this has been our "magic number" for defining output pixel sizes). However, the situation is slightly different if one considers that a printed colour orthophotograph must have the quality standards of the publishing industry or when the digital orthophotographs are used for on screen data collection and digitizing. In compiling the 1:50 000 scale map database for publishing and GIS applications, we immediately abandoned the 10 m per pixel of SPOT (an over coarse pixel size for the project) and moved to the 2·5 m per pixel black and white orthophotograph and, very recently, to the 1·8 m per pixel enhanced colour orthophotograph from the 1:60 000 scale photography. Comparing data capture times, we have measured an 8 per cent increase in productivity due to a better and faster identification (roughly 6 per cent because of the colour and 2 per cent due to the smaller pixel size). The overall improvement might seem rather modest, but it is important on an 18 man/year project.

Moving to an Integrated Environment

Digital photogrammetric stereoworkstations are very well tuned computer systems, capable of offering a great deal of computing power and fast access to data. For example, the Intergraph digital photogrammetric stereoworkstations equipped with an image processor (the Vitec-50) can speed up several basic operations. It implements smooth roaming and real time interpolated zooming during stereoplotting and takes care of all the pixel interpolations during image pyramid generation, epipolar sampling and orthophotograph generation. By using the image rectification software available on this processor, we have measured a speed up factor of 4 in CPU time† and a factor of 3 in total elapsed time (Table III). If one considers that the initial image file format translation is not necessary between the PS1 scanner and the Intergraph platforms, the improvement factor in elapsed time goes up to 5. In addition, if one takes advantage of colour image compression (three individually compressed components input and one colour compressed output), the factor reaches 6·5.

These results have triggered an internal debate as to whether we should fully implement the orthophotography workflow in the Intergraph environment. A key question for us is to know if the image processing functions implemented on the Vitec processor are rich enough to support our image enhancement processes with minor programming effort (just assembling command lines into a jobstream would be the ideal situation). Porting all our software from Vax/VMS to the Unix-based Intergraph system is out of the question since it would take a remarkable effort which would be better employed on research and development. In addition, there are some doubts about the convenience of writing software for systems with special hardware, especially if one considers that latest generation workstations are roughly four times faster in CPU when compared to our VaxStations 4000/90. On the other hand, we firmly believe that the real improvement comes from automation. For example, in orthophotography projects where no DTM is available, a good solution is to compile by image matching and surface reconstruction techniques, followed by quality control on a digital stereoworkstation. Initial tests with the Match-T surface generation software (Ackermann and Krzystek, 1991) show an elapsed time of 67 minutes for compiling 70 000 grid elevations from 30 μm epipolar images; the same task has taken 15 hours with the currently used procedures (profiles and breaklines). Therefore, we are now considering splitting the existing workflow into two parts. The first part would include all the tasks up to image rectification and would be carried out on the Intergraph system; the second part (image processing and mosaicking) would run on our own current environment. Digital point transfer and measurement is the natural consequence of this integrated approach; the digital mensuration software from Intergraph has been installed recently and is now being tested.

THE INTRODUCTION OF DIGITAL PHOTOGRAMMETRY IN STEREOPLOTTING

At the end of March 1994, the 4270 map sheets of the 1:5000 scale topographic map were finished. This map series has been produced since 1987 with computer assisted analogue stereoplotters. The first revision of this map series is scheduled to begin immediately. Included in the map revision is the updating of our elevation database used for the orthophotography projects. Long before, the decision to revise with stereoscopic superimposition had already been taken. Because no analytical stereoplotter with three dimensional superimposition was available in 1991 capable of working with our existing MicroStation files without format translations, the Zeiss/Intergraph PS1 scanner (Faust, 1989) and an Intermap digital stereoworkstation from Intergraph (Kaiser, 1991) were purchased and installed at the end of 1991.

The first generation of the Intermap system was not truly operational because of the lack of an accurate measurement cursor and because continuous panning was not available. Therefore we stopped our tests to await new hardware and software. In February 1993, our system was upgraded with a faster CPU and software for continuous

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†The colour case is particularly suited to this type of image computer since it uses parallel processing by devoting a dedicated image processor to each colour channel.

panning. In mid-April, the handheld photogrammetric cursor was installed and development resumed. During September 1993, the first digital stereoworkstation joined the production line for testing under production conditions. After three months in production, the results were good enough to order three more systems.

The Intergraph stereoworkstations are a good example of the upper range of digital photogrammetric systems. On the software side, one may find almost all the elements needed for photogrammetry, namely point mensuration and orientations, direct translators to and from popular aerial triangulation software, surface reconstruction by image matching, digital orthophotograph generation, image processing and, of course, stereoplotting. In addition they support a relational database for storing project-specific parameters including camera calibrations, image co-ordinates of measured points, ground control points and orientation parameters. On the hardware side, they have a very large high resolution screen (1664 × 1248 pixels), on the fly JPEG image compression, a fast CPU running under Unix and a specialized image computer (the Vitec-50) for smooth continuous panning of black and white and colour images and for image processing operations (pixel resampling and interpolations either off line or in real time during display). A more detailed description of the characteristics and performances of these systems was given by Colomer (1993).

Pixel Size

The 1:5000 scale topographic map series is based on our country-wide 1:22 000 scale black and white aerial photography taken by the latest generation of cameras with FMC and high resolution film. Once we started to define the proper pixel size for the project, we immediately realized that scanning at 15 μm (0·33 m pixel^{-1}) would probably fall short regarding the recommended pixel size for this scale[‡]. In order to obtain real facts, we did a test by stereoplotting the same area on a Leica SD2000 plotter and on the digital stereoworkstations with images scanned at 7·5 μm (0·165 m pixel^{-1}) and 15 μm. The site for the test was a rural and medium dense urban area. When we superimposed the results, no differences were found in the rural and open areas but minor discrepancies in the details were detected in dense urban areas. The discrepancies were considered to be of the same type as those one can find when two different operators collect features in the same area. Therefore, we decided to discard the 7·5 μm scans and to base the project on 15 μm pixel images. Larger photoscale images (1:12 000 to 1:15 000) at 15 μm will be used for dense urban areas.

Workflow

The present workflow starts, of course, with scanning. Since we are not using digital point transfer and digital mensuration of points yet, we still mark the positives artificially (PUG marking) and measure them on a Wild AC 1 analytical stereoplotter for further aerial triangulation. The orientation parameters from the bundle triangulation are used on the digital stereoworkstations directly after inner orientation; therefore, the operators do not perform relative and absolute orientation anymore. Epipolar sampling (Cho *et al.*, 1992) is performed with the orientation parameters of the bundle adjustment. One concern has been data management. In a digital photogrammetric environment, one must face the usual problems found in computer based environments: managing disk space, saving and restoring files and launching batch jobs. It has been clear to us that a stereoplotter operator should have these tasks eliminated as much as possible for smooth, comfortable and secure operation. Therefore we have implemented the concept of a "photogrammetric server" which is a stereoworkstation with large disk space devoted to storing the input images, the project files and databases and the models formed by two epipolar sampled images. When an operator requests a new model, the epipolar images are transferred to his workstation via Ethernet. He can then stereoplot and transfer the graphic file back to the server workstation and delete the model files. All

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[‡] Note that for 1:5000 scale, the German standard specifies 0·5 m lp^{-1} or 0·2 m pixel^{-1} using 2·5 pixels lp^{-1} as a conversion factor (Jacobsen, 1992). The USGS seems to be even more demanding when it sets 0·6 m pixel^{-1} for supporting digital stereoplotting from the National Aerial Photography Program at 1:40 000 scale (Light, 1993).

the files in the server are saved during the night in the central data archive. At present, the server workstation performs the epipolar sampling and will support digital point transfer and mensuration in the near future.

Ergonomics and Productivity

At the time we added the digital stereoworkstation to the production line our concerns were, among others, the operator's attitude towards the system, fatigue and/or eyestrain, the use of the handheld cursor instead of handwheels, the short delays during plotting because of loading new image tiles into the Vitec-50 for roaming or when building the roam vector display list (when changing zoom factor or enabling/disabling the display of feature levels) and graphic stereosuperimposition. Fortunately, none of these concerns has been a serious problem.

Initially, the operators asked for two 15 minute breaks during the 7·5 hours shift because of eyestrain and fatigue. An over intense and direct illumination in the workstation room was the cause. At present, they feel much more comfortable in a semi-dark room. They also quickly became used to the handheld cursor and the eyepieces used for stereovision and learned that superimposition could mislead them in cases where lines are snapped to the two dimensional projection of a three dimensional graphic element (overshooting effect in three dimensions). Pull down menus were abandoned in favour of the paper menus attached to the sensitive table of the stereoworkstation. Delays during stereoplotting are rare while capturing data because the operator roams at low speed and the system loads new image tiles in advance. Changes of the zoom factor or enabling/disabling feature levels do not occur very often.

Individual intensive training for the operators used to the analytical stereoplotters takes two days. Afterwards, it takes from two to three weeks until they become familiar with the stereoworkstations. During this adaptation period, the operators manipulate the system in quite an erratic way, causing the system to fail frequently. At this time, the operator attitude changes from lack of confidence to genuine appreciation once they become familiar with the system. The stereosuperimposition is by far the most well-liked feature.

Of course, the main question, which encompasses every other one, is productivity. Real figures comparing analytical stereoplotters and digital stereoworkstations are now available for the Pyrenees area. This area is dominated by complex topographic relief collected with profiles and breaklines from which contours are computed and checked off line in the case of the SD2000 analytical plotters, or computed and checked on line in the case of the stereoworkstations. Table IV compares both systems in terms of productivity of finished models (with contours computed and checked). Idle time because of rebooting after a system failure (down time) and contouring and checking time have been already added to the total time.

TABLE IV. Productivity summary for complete models (with contours).

System	*Total hours*	*Down (%)*	*Area (Ha)*	*Ha per hour with contouring*
Analytical	2341	0·0	46935	20·0
Digital (total 16 weeks)	772	11·7	14385	18·6
Digital (last 7 weeks)	344	3·2	7368	21·4

Note that we detail the results of the last seven weeks because a second workstation has since been devoted entirely to production. The down time percentage due to rebooting shows clearly the effects of our start up trials in which we were debugging our data capture software and doing training on the same workstation.

Steps to Follow: Integration and Automation

In a study comparing the operating costs of an analytical stereoplotter with optical superimposition with those of a digital stereoplotter, Schroth (1992) found a 30 per cent difference in favour of analytical plotters (at 1992 prices). The study did not include the

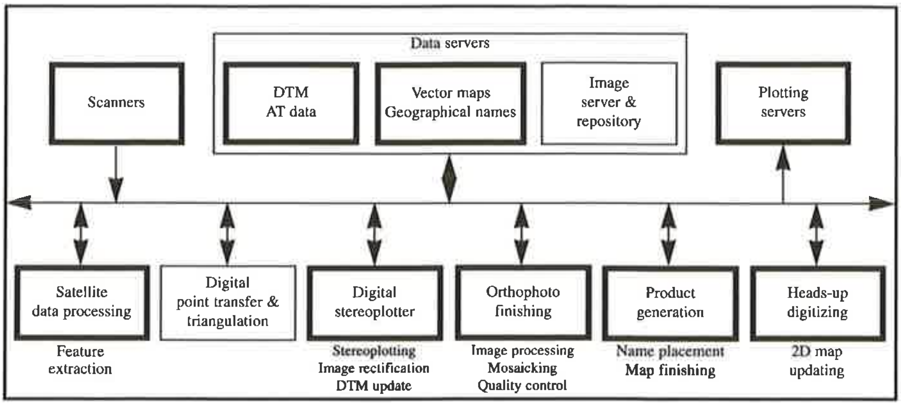

FIG. 1. ICC's system architecture for digital photogrammetry (1994).

costs of data management, the photoscanner and an output raster plotter¶. The productivity figures of Table IV confirm that the only chance of recovering the costs of a digital stereoplotting environment will come from reducing manual procedures. Photolaboratory processing is the first step that has already been substituted by the scan of negatives; the second one will be digital point transfer (Newby, 1990). Table V shows our planned workflow for the immediate future.

TABLE V. Planned production workflow.

Task	*Replaced by*
dodged positives	scanning negatives
pre-selection of points	digital point transfer (manual or semi-automatic)
point transfer and observation	digital point transfer (manual or semi-automatic)
aerial triangulation	not replaced
orientations (stereoplotting)	epipolar sampling (orientations from bundle adjustment)
stereoplotting	stereoplotting with stereosuperimposition
contour generation	not replaced
plotting for quality control	on line quality control using stereosuperimposition

However, operating in a computer based environment means the need for trained personnel for dealing with the initial system set up, testing of new features and software, the development of the methodologies, naming conventions and workflows and with the critical task of assuring operational continuity by resolving day to day troubles. We foresee the equivalent of at least one full person per year for supporting the digital photogrammetric environment. Furthermore, (semi-)automatic software uses parameters for tuning the results to different types of projects. Although manufacturers provide default values for these parameters and some hints on how to use them, one must try to achieve a deep knowledge of their behaviour with intensive testing by production staff and application specialists with knowledge of the theoretical foundations of the algorithms. In summary, we believe that stereoplotting with digital technology can probably be questioned in terms of its operating costs; in fact, stereoplotting has not achieved the levels of automation found in digital orthophotograph production yet.

BEYOND TRADITIONAL DIGITAL PHOTOGRAMMETRY AND REMOTE SENSING

A layout of the current (1994) architecture of our digital photogrammetric environment and some closely related subsystems is given in Fig. 1. The layout represents the current transition stage from analytical to digital photogrammetry. From a conceptual point of view, Fig. 1 represents a technological translation from the classical procedures to the corresponding digital versions. Though that is a very big step,

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¶Scanning and plotting services are starting to be offered in Spain at prices of $40 per black and white 15 μm scan and $80 for a raster plot on film.

because of our concurrent activities in remote sensing, we are in the process of developing new simpler and more general concepts. Certainly, in the realm of earth sciences, photogrammetry and remote sensing have long been close but largely independent specializations. Until recently, photogrammetry was expected to provide highly accurate data (in the geometric sense) for topographic maps at medium and large scales from film-based frame imagery. In contrast, remote sensing provided less accurate data for small scale thematic maps from digital line sensors. In the last decade, new technological tools have simplified many traditional time consuming or expensive procedures. Paramount examples are digital orthophotograph production and GPS aerial triangulation. With the increasing availability of new tools, there has been a concurrent increase of demands from a number of activity areas. These include environmental monitoring, forest inventory, impact assessment and natural disaster assessment to name only those of which we are aware. The corresponding new photogrammetric and remote sensing products often have new requirements. Radiometric accuracy may be more important than geometric accuracy. Fast product delivery may be critical. A hybrid photogrammetric and remote sensing product may be wanted. Examples related to the last statement are the use of airborne multispectral line scanners such as the Daedalus or the CASI or the use of very high altitude (satellite) analogue images.

The key to a rational approach to the exploitation of airborne and spaceborne imagery is the development of a global, unique concept which synthesizes the "remote sensing" and the "photogrammetric" points of view. Thus, a number of overlapping, similar or identical tasks and concepts will be classified in a single and comprehensive frame. These include among others digital photogrammetry and airborne remote sensing; satellite photogrammetry and spaceborne remote sensing; integrated sensor orientation, GPS aerial triangulation and combined block adjustment; epipolar resampling and geometric normalization; digital orthophotograph generation and satellite imagery topographic correction; satellite imagery registration; and radiometric enhancement and radiometric normalization. In the long term, the structure of organizations and the allocation of human resources have to be consistent with that concept.

It goes without saying that this synthesis can only be realized by a digital system. Indeed, the "confusion" requiring such a synthesis has somehow been produced by the collision or contact between traditional photogrammetry and remote sensing provoked by digital photogrammetry.

The basic hypothesis of our concept is that any image exploitation process consists of three main steps: data acquisition, sensor orientation and image interpretation. Acquisition of data refers to the acquisition of airborne or spaceborne imagery in both analogue and digital form as well as to the acquisition of additional observations for further sensor orientation; it also includes film development and scanning. Data acquisition tasks are becoming more and more complex and critical; modern aerial cameras are operated from computer systems, airborne digital sensors with particular calibration and operation procedures are already here, additional position and attitude determination systems have to be integrated with the imaging sensor systems and operated, and computer aided flight planning and flight execution (navigation) is finally a reality thanks to GPS. The same considerations for complexity also hold for scanning. The newly emerging data acquisition departments will require highly qualified engineers and technical staff.

Sensor orientation needs no description here. It includes conventional aerial triangulation, topographic surveying for ground control, modern GPS supported aerial triangulation and digital point transfer and single line and multiple line scanner orientation with position and/or attitude data either from airborne or spaceborne imagery. Images resampled to the normal case (a "normal case" has to be defined for each sensor geometry) might be the standard product of this step for further processing by interpretation specialists, no matter whether they are human beings or machines. In some cases ortho-images may also be the product. Modern general sensor orientation requires a clear understanding of geodetic position and attitude determination techniques and of sensor geometry and features. Even more than conventional aerial triangulation, sensor orientation is both geodesy and photogrammetry.

Once the orientation step has been concluded, the actual exploitation of images starts. In a very broad sense, we refer to this step as image interpretation where feature extraction and classification, again in a very broad sense, takes place. Examples include automatic or manual terrain surface reconstruction (DTM generation), stereocompilation of objects for topographic and cadastral mapping and thematic feature extraction for land use or environmental studies. Image interpretation is by far the most time consuming task and the one which can most benefit from automation.

ACKNOWLEDGEMENTS

The authors and the ICC would like to thank: Ms M. T. Torre, the software engineer in charge of the digital photogrammetric stereoworkstations project, for the excellent work done by her and for her unlimited devotion and attentiveness to the operators' suggestions; Mr. X. Alvaro, head of the Photogrammetry Department for his co-operation, enthusiasm and useful suggestions; and Ms M. L. Ibarra who was the first operator who started production and carried out all our trials with infinite patience.

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Résumé

L'Institut Cartographique de Catalogne s'est intéressé au traitement des images numériques depuis le moment où il a été crée, en 1982. Bien qu'au début les images numériques et leur technologie aient été réservées à la *télédétection, elles se sont trouvées peu à peu transférées et intégrées à la photogrammétrie. Ce savoir-faire a permis le développement des systèmes de télédétection et d'orthophotographie numérique et a, de plus, facilité la mise à disposition sur le marché de systèmes de photogrammétrie numérique qui sont maintenant pleinement opérationnels. On présente dans cet article l'expérience acquise dans le domaine du balayage, de la production des orthophotographies et de la stéréocompilation, on en tire quelques conclusions et l'on termine par un aperçu sur l'avenir de la photogrammétrie numérique.*

Zusammenfassung

Seit seiner Gründung im Jahre 1982 hat sich das Institut Cartogràfic de Catalunya mit digitalen Bildern beschäftigt. Obwohl digitale Bilder und Verfahren ursprünglich auf die Fernerkundung begrenzt waren, wurden sie schrittweise auf die Photogrammetrie übertragen bzw. mit ihr kombiniert. Zusätzlich zur Entwicklung von Fernerkundung und digitaler Orthophoto-Systeme hat diese Erfahrung die Einführung kommerziell verfügbarer digitaler photogrammetrischer Systeme erleichtert, die jetzt überall in der Praxis angewendet werden. Der Beitrag beschreibt die Erfahrung bei der Abtastung, der Herstellung von Orthophotos und bei der Stereoauswertung und gibt einige Schlußfolgerungen und Aussichten in bezug auf die Digitalphotogrammetrie wieder.

DISCUSSION

Chairman (Maj.-Gen. Wood): That was a fascinating account of the very impressive work that is done in your Institute. You've clearly built a great deal of experience over the years and you've actually attempted, and apparently succeeded in a number of cases, in many of the digital mapping problems which we all know exist. You've shown that, despite all the technology which is now available, it's by no means simple.

Mr. Newby: You mentioned in passing the DIAP lower cost workstation from ISM of Vancouver. You haven't said very much about your experience of that, except that you are looking to low cost systems for the future. You also say that you are looking to more automation in the future. Do you see those as the same path or are you going to have to choose, sooner or later, between automatic high cost systems and the manually operated low cost systems?

Mr. Colomer: I have a lot of respect for the people who have developed the DIAP because, with cheap and simple hardware, they have been able to put together a great number of features on a low cost platform, and to sell it. On the high cost side, the user is starting to see automatic tools coming from the academic world; for example, on Intergraph systems, Match-T and, to my understanding, fully automatic point transfer soon. Now, the question is to try to convince the people selling low cost systems to implement automatic software from elsewhere. If this happens, we will certainly try to move to the cheaper seats because of the maintenance costs of the high cost systems.

Chairman: At present, you have some experience with the high cost systems but you have not much experience with the others.

Mr. Colomer: This is correct and it is because, in its present status, the DIAP doesn't roam smoothly enough for comfortable stereoplotting. If I am allowed to give my own technical interpretation of this fact, I think that they probably have some bandwidth problems in the data transfer between memory and the graphics processor, or in the graphics processor performance. But they will succeed as hardware becomes faster. I am absolutely convinced that we will see the low cost systems grow. I look forward to seeing this happen. But then, probably, the people developing automatic software will charge us a lot more for the intelligence.

Mr. Farrow: You mentioned the JPEG compression. Is that hardwired or software?

Mr. Colomer: In fact, the JPEG is a standard.

Mr. Farrow: But is it on a chip or is it software?

Mr. Colomer: It is on hardware in the Intergraph implementation. It's a hardware board with a lot of chips that allows on the fly compression. You can have JPEG compression on a MacIntosh in software, but it's not real time.

Mr. Farrow: You have Match-T. Can that cope with irregular polygon areas yet or do the areas which you consider have to be squares or rectangles?

Mr. Colomer: You can define different regions with irregular polygons. This allows the application of different sets of control parameters for different types of terrain within a model. For example, you can use different parameters for mountainous terrain, for flat areas or for hilly areas.

Mr. Farrow: Is the PC a 66 MHz 486 or is it something less able?

Mr. Colomer: It is a PC. Our DIAP is configured with 64 Mb of memory. So it is a rather big PC.

Chairman: Do you expect to have much better cost effectiveness when you reach a revision stage and you can use the database that you've collected in your first cover? Is that really where you see advantages in using the digital systems or are you applying digital techniques despite the fact that it may be more expensive at present because you feel this is a good thing to do in itself?

Mr. Colomer: It takes us 15 hours to compile a dense DTM in complicated areas from a 1:60 000 photoscale model. For digital orthophotograph projects, Match-T delivers 70 000 elevation points in an hour. This is the easy part of the answer. The difficult part is to estimate the benefits in map revision. Mr. Newby is an expert on this topic. With stereosuperimposition, which is certainly not an exclusive feature of the digital systems, one can see very clearly errors and mismatches between the old data and the new photographs. So it is not just adding new features, but defining criteria which determine when to correct the errors. We also face a very particular problem, for in the past we decided to compile some features without true three dimensional graphic commands. This is the case with some linear features being at a constant *Z* value. Again, there is a decision to be made as to whether to correct or to leave those features uncorrected. I optimistically expect that correcting all the errors and updating with superimposition will take less than one half of the time it took us to compile the first cover.

Mr. Davies: I was interested in your accuracy tests with different pixel sizes. You showed us some graphic illustrations of planimetric discrepancies, but was there any work done on heighting differences?

Mr. Colomer: Not really. We have never done a systematic investigation on the accuracies at different pixel sizes, because we mainly concentrated on deciding a proper pixel size to identify and plot features. If you accept orientation residuals as a rough measure of accuracy, I can say that, with 15 μm, we regularly achieve the same residuals as with the SD2000 analytical plotter.

Chairman: It's been very good of you both to come and visit us. We have enjoyed the lecture and have been very impressed with all the things that you're doing. We congratulate you on that and wish you all the very best for future developments. I hope you'll come back in a few years' time and tell us more about it in due course. Thank you very much indeed.